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Abstract

Today's modern aircraft is based on air-breathing jet propulsion systems, which use moving fluids as substances to transform energy carried by the fluids into power. Throughout aero-vehicle evolution, improvements have been made to the engine efficiency and pollutants reduction.

The major advantages associated with the addition of ITB are an increase in thermal efficiency and reduction in NO_x emission. Lower temperature peak in the main combustor results in lower thermal NO_x emission and lower amount of cooling air required.

This study focuses on a parametric (on-design) cycle analysis of a dual-spool, separate-flow turbofan engine with an Interstage Turbine Burner (*ITB*). The *ITB* considered in this paper is a relatively new concept in modern jet engine propulsion. The *ITB* serves as a secondary combustor and is located between the high- and the low-pressure turbine, i.e., the transition duct.

The objective of this study is to use design parameters, such as flight Mach number, compressor pressure ratio, fan pressure ratio, fan bypass ratio, and high-pressure turbine inlet temperature to obtain engine performance parameters, such as specific thrust and thrust specific fuel consumption. Results of this study can provide guidance in identifying the performance characteristics of various engine components, which can then be used to develop, analyze, integrate, and optimize the system performance of turbofan engines with an *ITB*.

Visual Basic program, Microsoft® Excel macrocode, and Microsoft® Excel neuron code are used to facilitate Microsoft® Excel software to plot engine performance versus engine design parameters. This program computes and plots the data sequentially without forcing users to open other types of plotting programs. A user's manual on how to use the program is also included in this report.

Furthermore, this stand-alone program is written in conjunction with an off-design program which is an extension of this study. The computed result of a selected design-point engine will be exported to an engine reference data file that is required in off-design calculation.

Nomenclature

f	Fuel/air ratio
C_P	Specific heat at constant pressure
P_t	Total pressure
T_t	Total temperature
V	Absolute velocity

M	Mach number
a	Sound speed
g_c	Newton's constant
$\dot{m}$	Mass flow rate
R	Gas constant
T	Temperature, installed thrust
e	Polytropic efficiency
F	Force uninstalled thrust
S	Uninstalled trust specific fuel consumption
h_{PR}	Low heating value of fuel
$\dot{W}$	Power
α	Bypass ratio
γ	Ratio of specific heats
η	Efficiency
π	Total pressure ratio
τ	Total temperature ratio
τ_λ	Total enthalpy ratio
η_m	Mechanical Efficiency

Subscripts

itb	Inter-stage Turbine Combustors
b	Main burner
d	Diffuser
n	Nozzle
r	Ram
f	Fan
c	Properties between upstream and main burner
b	Properties between main burner exit and ITB
t	Properties between exit ITB and downstream, total
cL	Low pressure compressor
cH	High pressure compressor
tL	Low pressure turbine
tH	High pressure turbine
nf	Fan-Nozzle

1. Introduction

This program is designed to give a parametric cycle analysis of an ideal Turbo Fan air-breathing propulsion system. In most common air-breathing propulsion engines, the "heart" of a gas turbine is the gas generator. It consists of three major components namely, compressor, combustor, and turbine as shown in figure 1.1.

The idea behind gas generator is to convert intake air mixed with fuel into high temperature and high pressure gas. Depending on the applications of the gas turbine, the energy provided is extracted and used for different applications (turbojet, turbofan, turbo-shaft, turboprop, and ramjet) through different mechanisms. A turbojet engine can be constructed by adding an inlet and a nozzle as shown in figure 1.2.
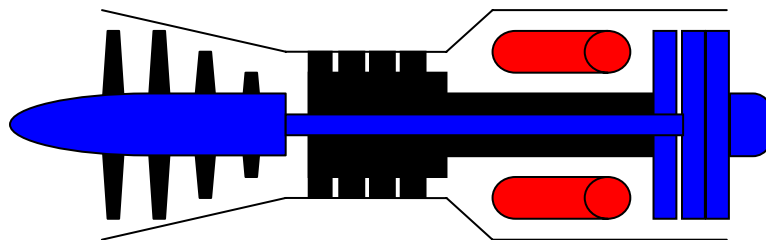
Figure 1.1.—A Gas Generator Propulsion System
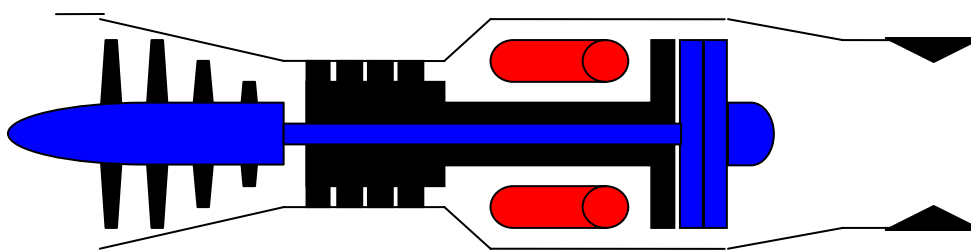
Figure 1.2.—Schematic Diagram for Turbojet Engine

The nozzle converts internal energy of the hot gas into kinetic energy or a thrust. The work extracted by the turbine is used to drive the compressor. In the case of turbofan, turboprop, and turbo-shaft, the work from the turbine is required to drive a shaft for turbo-shaft, a fan for turbofan, and a propeller for turboprop in addition to drive the compressor. The ramjet engine consists of an inlet, a combustor, and a nozzle at the exit. It does not require the compressor because the inlet already has an air-compressing mechanism such that intake air has sufficient kinetic energy to increase its pressure.

The main objective of this analysis it to determine the relationships between engine performance (primarily thrust F, thrust specific fuel S) to design parameters (compressor pressure ratio, fan pressure ratio, bypass ratio, etc.), to design constraints (burner exit temperature, compressor exit pressure, etc.), and to flight environment (Mach number, ambient temperature, ambient pressure, etc.).

2. Aircraft Engine Parameters

2.1 Performance Parameters

2.1.1 Thrust.—Thrust is the force used to sustain the flight (thrust = drag), accelerate flight (thrust > drag), decelerate flight (thrust < drag). Using figure 3.1 for the control volume, we can apply momentum balance to the control volume. Uninstalled thrust F of a jet engine (single inlet and single exhaust) is given by

$$F = \frac{\left(\dot{m}_0 + \dot{m}_{fuel}\right)V_e - \dot{m}_0 V_0}{g_c} + \left(P_e - P_0\right)A_e \tag{1.1}$$

where $\dot{m}_o, \dot{m}_f$ are mass flow rates of air and fuel respectively

V_o, V_e are velocities at inlet and exit respectively

P_o, P_e are pressure at inlet and exit respectively

For ideal case, the hot gas is expanded to the ambient pressure which gives $P_e = P_0$. Equation (1.1) becomes

$$F = \frac{(\dot{m}_0 + \dot{m}_{fuel})V_e - \dot{m}_0 V_0}{g_c}$$

(1.2)

The installed thrust T is given by

$$T = F - D_{inlet} - D_{noz}$$

(1.3)

where D_{inlet} and D_{noz} are the drag force from the inlet and the nozzle.

2.1.2 Specific Fuel Consumptions.—It is the rate of fuel use by the propulsion system per unit of thrust produced. The installed specific fuel consumptions, *TSFC*, and uninstalled specific fuel consumptions, *S*, are given by

$$TSFC = \frac{\dot{m}_f}{T}$$

(1.4)

$$S = \frac{\dot{m}_f}{F}$$

(1.5)

2.1.3 Efficiencies of an Engine.—Some of the following parameters will be used widely in this program namely, thermal efficiency, propulsive efficiency, and overall efficiency.

The *thermal efficiency* characterizes the net energy output extracted (shaft work) from the engine divided by the available thermal energy (fuel).

$$\eta_{TH} = \frac{\dot{W}_{out}}{\dot{Q}_{in}}$$

(1.6)

where,

η_{TH} = thermal efficiency

$\dot{W}_{out}$ = net power out of engine

$\dot{Q}_{in}$ = rate of thermal energy released $(\dot{m}_f h_{PR})$

The *propulsive efficiency* defines the ratio between the engine power output and the power being used to run the aircraft.

$$\eta_P = \frac{T \cdot V_0}{\dot{W}_{out}}$$

(1.7)

where,

η_P =   propulsive efficiency of engine

T =   thrust of propulsion system

V_0 =   velocity of aircraft

$\dot{W}_{out}$ =   net power out of engine

An overall performance of a propulsion system is given by the combination between thermal and propulsive efficiencies.

$$\eta_O = \eta_P\, \eta_{TH} \tag{1.8}$$

where,

η_O is overall efficiency.

2.2 Notations for Compressible Flow

Some useful quantity notation for compressible flow will be used in this report namely, stagnation temperature, stagnation pressure, and Mach number.

Stagnation temperature or total temperature T_t is defined as the temperature obtained when steadily flowing fluid is brought to rest adiabatically without involvement of works. Applying first law of thermodynamic to calorically perfect gas gives:

$$h_e = h_i = h_t = h + \frac{V^2}{2} \tag{1.9}$$

where,

h_t is the enthalpy at stagnation condition.

With the assumptions constant specific heat coefficient, the above equation can be written as:

$$T_t = T + \frac{V^2}{2c_p} = T\left(1 + \frac{\gamma - 1}{2}M^2\right) \tag{1.10}$$

where,

T_t =   stagnation temperature

T =   static temperature

M =   Mach number

γ =   ratio of specific heats

Stagnation pressure or total pressure P_t is defined as pressure reached when a steady flowing fluid is brought to rest adiabatically and reversibly. Using the isentropic relation, total pressure is given by

$$P_t = P\left(1 + \frac{\gamma - 1}{2} M^2\right)^{\frac{\gamma}{\gamma - 1}} \tag{1.11}$$

Ratio of total temperatures τ and ratio of total pressure π across a component are denoted by subscript: d for diffuser, cL for low-pressure compressor, cH for high-pressure compressor, b for main burner, ITB for inter-stage turbine burner, tH for low-pressure turbine, tH for high-pressure turbine, n for nozzle, nf for fan nozzle, and f for fan. For example:

$$\pi_d = \frac{\text{total pressure leaving diffuser}}{\text{total pressure entering diffuser}} \tag{1.12}$$

$$\tau_d = \frac{\text{total temperature leaving diffuser}}{\text{total temperature entering diffuser}} \tag{1.13}$$

2.3 Exceptions

For the free stream, ram, we define τ_r as a ratio of total temperature to static temperature and π_r as a ratio of total pressure to static pressure.

$$\tau_r = \frac{T_{t0}}{T_0} = 1 + \frac{\gamma - 1}{2} M_0^2 \tag{1.14}$$

$$\pi_r = \frac{P_{t0}}{P_0} = \left(1 + \frac{\gamma - 1}{2} M_0^2\right)^{\gamma/(\gamma - 1)} \tag{1.15}$$

A ratio between total enthalpy of the burner exit and ambient enthalpy, denoted by τ_λ, is defined such that it will be one of the input parameters:

$$\tau_{\lambda-b} = \frac{\left(c_p T_t\right)_{burner\,exit}}{\left(c_p T\right)_{0,ambient}} \tag{1.16}$$

$$\tau_{\lambda-itb} = \frac{\left(c_p T_t\right)_{ITB\,exit}}{\left(c_p T\right)_{0,ambient}} \tag{1.17}$$

2.4 Component Performance

In this analysis, it is acceptable to assume that the working fluid in the engine can be idealized as a perfect gas. Properties of an ideal gas strongly depend on the temperature. This cycle allows fluid properties variation across the engine which assumes constant fluid properties from the main burner entrance upstream (c_{pc}, γ_c), from ITB entrance to main burner exit (c_{pt}, γ_t), and from ITB exit downstream (c_{pitb}, γ_{itb}).

2.4.1 Inlet and Diffuser.—Pressure losses occur due to the friction within the inlet wall. The pressure total ratio, π_d, is always less than 1.

In supersonic flight, the pressure losses cause shock waves which produce greater pressure losses. The inlet total pressure is defined as the product of the ram pressure ratio and the diffuser pressure ratio. Therefore the portion of the pressure losses due to the wall friction and the shock waves is defined by:

$$\pi_d = \pi_{d\,max}\ \eta_r \tag{1.18}$$

From the Military Specification 5008B [1], the following relation is obtained:

$$
\begin{aligned}
\eta_r &= 1 & \text{for} \quad & M_0 \le 1 \\
\eta_r &= 1 - 0.075(M_0 - 1)^{1.35} & \text{for} \quad & 1 < M_0 < 5 \\
\eta_r &= \frac{800}{M_0^4 + 935} & \text{for} \quad & M_0 > 5
\end{aligned}
\tag{1.19}
$$

2.4.2 Compressor and Turbine.—Compressor is measured through two types of efficiencies, namely, isentropic efficiency and polytropic efficiency. *Isentropic efficiency* is defined by

$$\eta_c = \frac{\text{ideal work of compression for given } \pi_c}{\text{actual work of compression for given } \pi_c} \tag{1.20}$$

$$\eta_c = \frac{\pi_c^{(\gamma-1)/\gamma} - 1}{\tau_c - 1} \tag{1.21}$$

Polytropic efficiency is defined as

$$e_c = \frac{\text{ideal work of compression for a differential pressure change}}{\text{actual work of compression for a differential pressure change}} \tag{1.22}$$

With the assumption of constant e_c, we can obtain the relation between τ_c and π_c:

$$\tau_c = \pi_c^{(\gamma-1)/(\gamma e_c)} \tag{1.23}$$

Going through similar procedure as the compressor, we obtain turbine isentropic efficiency, turbine polytropic efficiency and relation between τ_t and π_t as follows:

$$\eta_t = \frac{\text{ideal turbine work for given } \pi_t}{\text{actual turbine work for given } \pi_t} \tag{1.24}$$

$$\eta_t = \frac{1 - \tau_t}{1 - \pi_t^{(\gamma-1)/\gamma}} \tag{1.25}$$

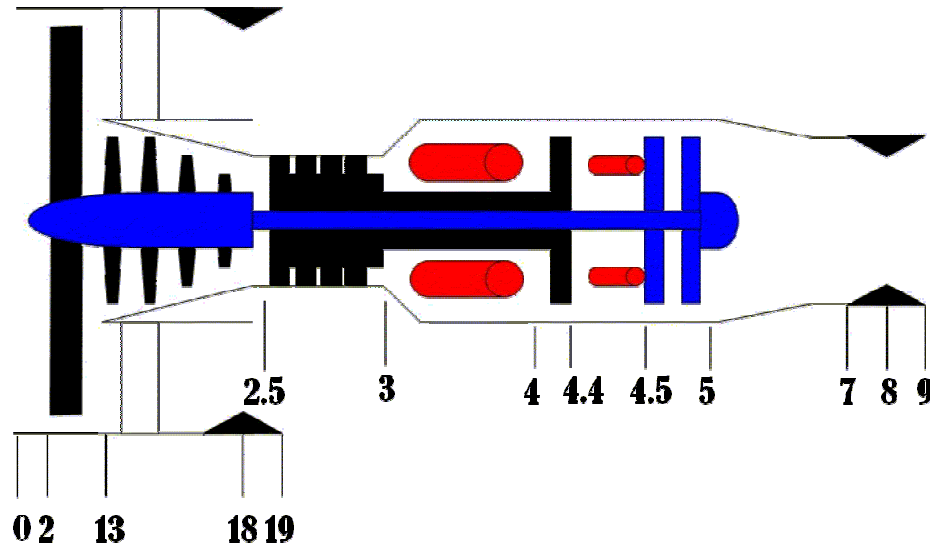$$\pi_t = \tau_t^{\gamma/(\gamma-1)e_t} \tag{1.26}$$

Figure 3.1.—Station numbering of a turbofan engine with *ITB*.

3. TurboFan—Separate Exhaust Streams with ITB Cycle Analysis

The station numbering for the turbofan cycle analysis with *ITB* is in accordance with APR 755A [2] and is given in figure 3.1. The *ITB* is located between station 4.4 and 4.5.

The air stream entering the turbofan engine will flow through the fan and the engine core separately. Cycle analysis is then applied to both the bypass stream and engine core stream separately as listed below. The analysis follows closely as described in Mattingly [3].

3.1 Assumptions

The following assumptions are employed:

1. Perfect gas upstream of main burner with constant properties γ_c, R_c, c_{pc}
2. Perfect gas between station four and five with constant properties γ_t, R_t, c_{pt}
3. Perfect gas downstream of inter-stage burner with constant properties γ_{itb}, R_{itb}, c_{pitb}
4. All components are adiabatic
5. The efficiencies of the high-pressure compressor (*HPC*), low-pressure compressor (*LPC*), fan, high-pressure turbine (*HPT*), and low-pressure turbine (*LPT*) are described through the use of polytropic efficiencies, i.e., e_{cH}, e_{cL}, e_f, e_{tH}, and e_{tL}, respectively.

3.2 Fan Stream

Step 1.—Uninstalled thrust of fan stream, F_f, is given by

$$F_f = \frac{\dot{m}_f}{g_c}\left(V_{19} - V_0\right) + \left(P_{19} - P_0\right)A_{19} \tag{3.1}$$

Rearranging equation (3.1) gives:

$$\frac{F_f}{\dot{m}_f} = \frac{a_0}{g_c}\left(\frac{V_{19}}{a_0} - M_0 + \frac{T_{19}/T_0}{V_{19}/a_0}\frac{1 - P_0/P_{19}}{\gamma_c}\right) \tag{3.2}$$

Step 2.—

$$\left(\frac{V_{19}}{a_0}\right)^2 = \frac{a_{19}^2\,M_{19}^2}{a_0^2} = \frac{T_{19}}{T_0}M_{19}^2 \tag{3.3}$$

Step 3.—

$$M_{19} = \sqrt{\frac{2}{\gamma_c - 1}\left[\left(\frac{P_{t19}}{P_{19}}\right)^{(\gamma_c - 1)/\gamma_c} - 1\right]} \tag{3.4}$$

where

$$\frac{P_{t19}}{P_{19}} = \frac{P_0}{P_{19}}\,\pi_r\,\pi_d\,\pi_f\,\pi_{nf} \tag{3.4a}$$

Step 4.—

$$\frac{T_{19}}{T_0} = \frac{T_{t19}\big/T_0}{T_{t19}\big/T_{19}} = \frac{T_{t19}\big/T_0}{\left(P_{t19}\big/P_{19}\right)^{(\gamma_c - 1)/\gamma_c}} \tag{3.5}$$

where

$$\frac{T_{t19}}{T_0} = \tau_r\,\tau_f \tag{3.5a}$$

3.3 Engine Core Stream

Step 1.—Uninstalled thrust

$$F_c = \frac{1}{g_c}\left(\dot{m}_9\,V_9 - \dot{m}_0\,V_0\right) + \left(P_9 - P_0\right)A_9 \tag{3.6}$$

Rearranging equation (3.6) gives:

$$\frac{F_c}{\dot{m}_0} = \frac{a_0}{g_c}\left(\frac{\dot{m}_9}{\dot{m}_c}\frac{V_9}{a_0} - M_0\right) + \frac{A_9\,P_9}{\dot{m}_c}\left(1 - \frac{P_0}{P_9}\right) \tag{3.7}$$

Step 2.—

$$\frac{\dot{m}_9}{\dot{m}_c} = 1 + f \tag{3.8}$$

where

$$\dot{m}_9 = \dot{m}_c + \dot{m}_b + \dot{m}_{itb} \tag{3.8a}$$

$$f = f_b + f_{itb} \tag{3.8b}$$

$$f_b = \frac{\dot{m}_b}{\dot{m}_c} \tag{3.8c}$$

$$f_{itb} = \frac{\dot{m}_{itb}}{\dot{m}_c} \tag{3.8d}$$

Step 3.—Multiplying $\dfrac{A_9 P_9}{\dot{m}_c}\left(1 - \dfrac{P_0}{P_9}\right)$ by $\dfrac{\dot{m}_9}{\rho_9 \, A_9 \, V_9}\dfrac{a_0 \, a_0}{\gamma_c \, R_c \, T_0}$ and rearranging gives:

$$\frac{A_9 P_9}{\dot{m}_c}\left(1 - \frac{P_0}{P_9}\right) = (1 + f)\frac{R_{itb}}{R_c}\frac{T_9/T_0}{V_9/a_0}\frac{a_0}{g_c}\left(1 - \frac{P_0}{P_9}\right)\frac{1}{\gamma_c} \tag{3.9}$$

Step 4.—Uninstalled thrust for the engine core becomes:

$$\frac{F_c}{\dot{m}_c} = \frac{a_0}{g_c}\left[(1 + f)\frac{V_9}{a_0} - M_0 + (1 + f)\frac{R_{itb}}{R_c}\frac{T_9/T_0}{V_9/a_0}\left(1 - \frac{P_0}{P_9}\right)\frac{1}{\gamma_c}\right] \tag{3.10}$$

Step 5.—

$$\left(\frac{V_9}{a_0}\right)^2 = M_9^2 \, \frac{\gamma_{itb} \, R_{itb} \, T_9}{\gamma_c \, R_c \, T_0} \tag{3.11}$$

From the total pressure and Mach number relation,

$$M_9 = \sqrt{\frac{2}{\gamma_{itb} - 1}\left[\left(\frac{P_{t9}}{P_9}\right)^{(\gamma_{itb} - 1)/\gamma_{itb}} - 1\right]} \tag{3.12}$$

$$\frac{T_9}{T_0} = \frac{T_{t9}/T_0}{T_{t9}/T_9} = \frac{T_{t9}/T_0}{\left(P_{t9}/P_9\right)^{(\gamma_{itb} - 1)/\gamma_{itb}}} \tag{3.13}$$

where

$$\frac{P_{t9}}{P_9} = \pi_r\,\pi_d\,\pi_{cL}\,\pi_{cH}\,\pi_b\,\pi_{tH}\,\pi_{itb}\,\pi_{tL}\,\pi_n \tag{3.13a}$$

$$\frac{T_{t9}}{T_0} = \tau_r\,\tau_d\,\tau_c\,\tau_b\,\tau_{tH}\,\tau_{itb}\,\tau_{tL}\,\tau_n \tag{3.13b}$$

$$\tau_d = 1 \tag{3.13c}$$

$$\tau_n = 1 \tag{3.13d}$$

$$\tau_b = \frac{T_{t4}}{T_0\,\tau_r\,\tau_{cH}\,\tau_{cL}} \tag{3.13e}$$

Step 6.—Apply First Law of Thermodynamics and ideal gas relation to the main burner:

$$\dot{m}_c\,c_{pc}\,T_{t3} + \dot{m}_b\,\eta_b\,h_{PR-b} = \dot{m}_4\,c_{pt}\,T_{t4} \tag{3.14}$$

Multiply the above equation with $\dfrac{T_{t0}}{\dot{m}_c\,c_{pc}\,T_0\,T_{t2}}$, rearrange gives:

$$\tau_c\,\tau_r + \frac{\eta_b\,h_{PR-b}\,f_b}{c_{pc}\,T_0} = (1 + f_b)\tau_{\lambda-b} \tag{3.15}$$

Solve for f_b:

$$f_b = \frac{\tau_{\lambda-b} - \tau_r\tau_{cL}\tau_{cH}}{\eta_b h_{PR}/(c_{pc}T_0) - \tau_{\lambda-b}} \tag{3.16}$$

where

$$\tau_{\lambda-b} = \frac{C_{pt}\,T_{t4}}{C_{pc}\,T_0} \tag{3.16a}$$

$$T_{t0} = T_{t2} \quad \text{(for the case adiabatic)} \tag{3.16b}$$

$$\tau_c = \tau_{cH}\,\tau_{cL} \tag{3.16c}$$

Step 7.—Apply First Law of Thermodynamics and ideal gas relation to the *ITB*:

$$\dot{m}_4\,c_{pt}\,T_{t4.4} + \dot{m}_{itb}\,\eta_{itb}\,h_{PR-itb} = \dot{m}_{4.5}\,c_{pitb}\,T_{t4.5} \tag{3.17}$$

Rearranging the above equation gives,

$$f_{itb} = (1 + f_b) \frac{\tau_{\lambda-itb} - \tau_{\lambda-b}\tau_{tH}}{\eta_{itb}h_{PR}/(c_{pc}T_0) - \tau_{\lambda-itb}} \tag{3.18}$$

where

$$\tau_{\lambda-itb} = \frac{C_{pitb} \, T_{t4.5}}{C_{pc} \, T_0} \tag{3.18a}$$

$$T_{t9} = T_{t5} \text{ (for the adiabatic case)} \tag{3.18b}$$

$$\tau_c = \tau_{cH} \, \tau_{cL} \tag{3.18c}$$

Step 8.—Apply first law to each individual compressors and turbines:

$$\text{Power balance for } \textit{LPC:} \quad \dot{W}_{cL} = \dot{m}_c \, c_{pc} \left(T_{t2.5} - T_{t2}\right) \tag{3.19}$$

$$\text{Power balance for } \textit{HPC:} \quad \dot{W}_{cH} = \dot{m}_c \, c_{pc} \left(T_{t3} - T_{t2.5}\right) \tag{3.20}$$

$$\text{Power balance for } \textit{HPT:} \quad \dot{W}_{tH} = \dot{m}_4 \, c_{pt} \, \eta_{m-HP} \left(T_{t4} - T_{t4.4}\right) \tag{3.21}$$

$$\text{Power balance for } \textit{LPT:} \quad \dot{W}_{tL} = \dot{m}_{4.5} \, c_{pitb} \, \eta_{m-LP} \left(T_{t4.5} - T_{t5}\right) \tag{3.22}$$

$$\text{Power balance for fan:} \quad \dot{W}_f = \dot{m}_f \, c_{pc} \left(T_{t13} - T_{t2}\right) \tag{3.23}$$

It is chosen that the *HPT* and *HPC* are connected by a single shaft; therefore ideal turbofan the relation is given by:

$$\dot{W}_{cH} = \dot{W}_{tH} \tag{3.24}$$

Multiplying both sides of equation (3.24) with $\dfrac{1}{\dot{m}_c \, c_{pc} \, T_{t2.5}}$ gives:

$$(\tau_{cH} - 1) = \frac{c_{pt}}{c_{pc}} (1 + f_b)\tau_{cH} \, \tau_b \, \eta_{m-HP} \left(1 - \tau_{tH}\right) \tag{3.25}$$

Solve for τ_{tH}:

$$\tau_{tH} = 1 + \frac{1 - \tau_{cH}}{(1 + f_b)\dfrac{c_{pt}}{c_{pc}} \tau_{cH} \, \tau_b \, \eta_{m-HP}} \tag{3.26}$$

where

$$\tau_b = \frac{T_{t4}}{T_0 \, \tau_r \, \tau_c} \tag{3.26a}$$

LPT, *LPC*, and the fan are connected by a single shaft; therefore ideal turbofan, the relation is given by:

$$\dot{W}_{cL} + \dot{W}_f = \dot{W}_{tL} \tag{3.27}$$

Multiplying both sides of equation (3.27) with $\dfrac{1}{\dot{m}_c \, c_{pc} \, T_{t2}}$ gives:

$$(\tau_{cL} - 1) + \alpha (\tau_f - 1) = \frac{c_{pitb}}{c_{pc}} (1 + f) \frac{T_{t4.5}}{T_{t2}} \eta_{m-LP} (1 - \tau_{tL}) \tag{3.28}$$

Solve for τ_{tL}:

$$\tau_{tL} = 1 + \frac{1 - \tau_{cL} + \alpha (1 - \tau_f)}{(1 + f) \dfrac{c_{pitb}}{c_{pc}} \dfrac{T_{t4.5}}{T_{t2}} \eta_{m-LP}} \tag{3.29}$$

where

$$\frac{T_{t4.5}}{T_{t2}} = \tau_{cL} \, \tau_{cH} \, \tau_b \, \tau_{tH} \, \tau_{itb} \tag{3.29a}$$

$$\tau_{itb} = \frac{T_{t4.5}}{T_0 \, \tau_r \, \tau_c \, \tau_b \, \tau_{tH}} \tag{3.29b}$$

Step 9.—Total uninstalled thrust per unit mass flow rate intake is given by:

$$\frac{F}{\dot{m}_0} = \frac{\dfrac{F_c}{\dot{m}_c} + \alpha \dfrac{F_f}{\dot{m}_f}}{(1 + \alpha)} \tag{3.30}$$

Step 10.—Thrust specific fuel consumption (*S*) is given by:

$$S = \frac{f_b + f_{itb}}{(1 + \alpha) \dfrac{F}{\dot{m}_0}} \tag{3.31}$$

4. Summary of Equations

All equations below are executed and computed in subroutine *itb()* inside Module 1 of Microsoft Visual Basic. The flow chart of this subroutine can be found in figure B.5 in appendix B. These equations are solved sequentially, except for *MSH* fuel burn model, which is solved by using *successive substitution* method.

Inputs: M_0, T_0, γ_c, c_{pc}, γ_t, c_{pt}, γ_{itb}, c_{pitb}, h_{PR-b}, h_{PR-itb}, $\pi_{d\,max}$, π_b, π_{itb}, π_n, π_{nf}, e_{cH}, e_{cL}, e_f, e_{tH}, e_{tL}, η_b, η_{itb}, η_{m-HP}, η_{m-LP}, P_0/P_9, P_0/P_{19}, T_{t4}, $T_{t4.5}$, π_{cH}, π_{cL}, π_f, α

Outputs: $F/\dot{m}$, S, f

Equations:

$$R_c = \frac{\gamma_c - 1}{\gamma_c} c_{pc} \tag{4.1}$$

$$R_t = \frac{\gamma_t - 1}{\gamma_t} c_{pt} \tag{4.2}$$

$$R_{itb} = \frac{\gamma_{itb} - 1}{\gamma_{itb}} c_{pitb} \tag{4.3}$$

$$a_0 = \sqrt{\gamma_c R_c g_c T_0} \tag{4.4}$$

$$V_0 = M_0 a_0 \tag{4.5}$$

$$\tau_r = 1 + \frac{\gamma_c - 1}{2} M_0^2 \tag{4.6}$$

$$\pi_r = \tau_r^{\gamma_c/(\gamma_c - 1)} \tag{4.7}$$

$$\begin{aligned}
\eta_r &= 1 & \text{for} \quad M_0 \leq 1 \\
\eta_r &= 1 - 0.075(M_0 - 1)^{1.35} & \text{for} \quad 1 < M_0 < 5 \\
\eta_r &= \frac{800}{M_0^4 + 935} & \text{for} \quad M_0 > 5
\end{aligned} \tag{4.8}$$

$$\pi_d = \pi_{d\,max} \eta_r \tag{4.9}$$

$$\tau_{\lambda-b} = \frac{C_{pt} T_{t4}}{C_{pc} T_0} \tag{4.10}$$

$$\tau_{\lambda-itb} = \frac{C_{pitb} T_{t4.5}}{C_{pc} T_0} \tag{4.11}$$

$$\tau_{cH} = \pi_{cH}^{(\gamma_c - 1)/(\gamma_c e_{cH})} \tag{4.12}$$

$$\tau_{cL} = \pi_{cL}^{(\gamma_c - 1)/(\gamma_c \, e_{cL})} \tag{4.13}$$

$$\tau_f = \pi_f^{(\gamma_c - 1)/(\gamma_c \, e_f)} \tag{4.14}$$

$$\tau_c = \tau_{cH} \tau_{cL} \tag{4.15}$$

$$\tau_b = \frac{T_{t4}}{T_0 \tau_r \tau_c} \tag{4.16}$$

$$\eta_{cH} = \frac{\tau_{cH}^{e_{cH}} - 1}{\tau_{cH} - 1} \tag{4.17}$$

$$\eta_{cL} = \frac{\tau_{cL}^{e_{cL}} - 1}{\tau_{cL} - 1} \tag{4.18}$$

$$\eta_f = \frac{\tau_f^{e_f} - 1}{\tau_f - 1} \tag{4.19}$$

If CSH model then

$$f_b = \frac{\tau_{\lambda-b} - \tau_r \tau_{cL} \tau_{cH}}{\eta_b h_{PR} / (c_{pc} T_0) - \tau_{\lambda-b}} \tag{4.20a}$$

Else

$$T_{t3} = T_0 \tau_r \tau_{cL} \tau_{cH} \tag{4.20b}$$

ENTHALPY $\left(T_{t3}, 0, h_{t3} \right)$

Set initial value of fuel/air ratio at station 4,

$$f_{4i} = \frac{\tau_{\lambda-b} - \tau_r \tau_{cL} \tau_{cH}}{\eta_b h_{PR} / (c_{pc} T_0) - \tau_{\lambda-b}} \tag{4.20c}$$

3 ENTHALPY $\left(T_{t4}, f_{4i}, h_{t4} \right)$

$$f_b = \frac{h_{t4} - h_{t3}}{\eta_b h_{PR} - h_{t4}} \tag{4.20d}$$

If $\left| f_b - f_{4i} \right| > 0.0001$, then $f_{4i} = f_b$ and go to 3; else continue.

End if

$$\tau_{tH} = 1 + \frac{1 - \tau_{cH}}{(1 + f_b) \dfrac{c_{pt}}{c_{pc}} \tau_{cH} \, \tau_b \, \eta_{m-HP}} \tag{4.21}$$

If CSH model then

$$f_{itb} = (1 + f_b) \frac{\tau_{\lambda-itb} - \tau_{\lambda-b}\tau_{tH}}{\eta_{itb}h_{PR} / (c_{pc}T_0) - \tau_{\lambda-itb}}$$ (4.22a)

Else

$$T_{t4.4} = T_{t4}\tau_{tH}$$ (4.22b)

ENTHALPY $(T_{t4.4}, f_b, h_{t4.4})$
Set initial value of fuel/air ratio at station 4.4,

$$f_{4.5i} = (1 + f_b) \frac{\tau_{\lambda-itb} - \tau_{\lambda-b}\tau_{tH}}{\eta_{itb}h_{PR} / (c_{pc}T_0) - \tau_{\lambda-itb}}$$ (4.22c)

4 ENTHALPY $(T_{t4.5}, f_{4.5i}, h_{t4.5})$

$$f_{itb} = (1 + f_b) \frac{h_{t4.5} - h_{t4.4}}{\eta_{itb}h_{PR} - h_{t4.5}}$$ (4.22d)

If $|f_b + f_{itb} - f_{4.5i}| > 0.0001$, then $f_{4.5i} = f_b + f_{itb}$ and go to 4; else continue.
End if

$$f = f_b + f_{itb}$$ (4.23)

$$\tau_{itb} = \frac{T_{t4.5}}{T_0 \, \tau_r \, \tau_c \, \tau_b \, \tau_{tH}}$$ (4.24)

$$\frac{T_{t4.5}}{T_{t2}} = \tau_{cL} \, \tau_{cH} \, \tau_b \, \tau_{tH} \, \tau_{itb}$$ (4.25)

$$\tau_{tL} = 1 + \frac{1 - \tau_{cL} + \alpha(1 - \tau_f)}{(1 + f) \frac{c_{pitb}}{c_{pc}} \frac{T_{t4.5}}{T_{t2}} \eta_{m-LP}}$$ (4.26)

$$\pi_{tH} = \tau_{tH}^{\gamma_t / [(\gamma_t - 1)e_{tH}]}$$ (4.27)

$$\pi_{tL} = \tau_{tL}^{\gamma_{itb} / [(\gamma_{itb} - 1)e_{tL}]}$$ (4.28)

$$\eta_{tH} = \frac{1 - \tau_{tH}}{1 - \tau_{tH}^{1/e_{tH}}}$$ (4.29)

$$\eta_{tL} = \frac{1 - \tau_{tL}}{1 - \tau_{tL}^{1/e_{tL}}}$$ (4.30)

$$\frac{P_{t9}}{P_9} = \pi_r \, \pi_d \, \pi_{cL} \, \pi_{cH} \, \pi_b \, \pi_{tH} \, \pi_{itb} \, \pi_{tL} \, \pi_n$$ (4.31)

$$\frac{T_{t9}}{T_0} = \tau_r \, \tau_c \, \tau_b \, \tau_{tH} \, \tau_{itb} \, \tau_{tL} \tag{4.32}$$

$$\frac{T_9}{T_0} = \frac{T_{t9}/T_0}{T_{t9}/T_9} = \frac{T_{t9}/T_0}{\left(P_{t9}/P_9\right)^{(\gamma_{itb}-1)/\gamma_{itb}}} \tag{4.33}$$

$$M_9 = \sqrt{\frac{2}{\gamma_{itb}-1}\left[\left(\frac{P_{t9}}{P_9}\right)^{(\gamma_{itb}-1)/\gamma_{itb}} - 1\right]} \tag{4.34}$$

$$\frac{V_9}{a_0} = M_9 \sqrt{\frac{\gamma_{itb} \, R_{itb} \, T_9}{\gamma_c \, R_c \, T_0}} \tag{4.35}$$

$$\frac{P_{t19}}{P_{19}} = \frac{P_0}{P_{19}} \pi_r \, \pi_d \, \pi_f \, \pi_{nf} \tag{4.36}$$

$$M_{19} = \sqrt{\frac{2}{\gamma_c-1}\left[\left(\frac{P_{t19}}{P_{19}}\right)^{(\gamma_c-1)/\gamma_c} - 1\right]} \tag{4.37}$$

$$\frac{T_{t19}}{T_0} = \tau_r \, \tau_f \tag{4.38}$$

$$\frac{T_{19}}{T_0} = \frac{T_{t19}/T_0}{T_{t19}/T_{19}} = \frac{T_{t19}/T_0}{\left(P_{t19}/P_{19}\right)^{(\gamma_c-1)/\gamma_c}} \tag{4.39}$$

$$\frac{V_{19}}{a_0} = \frac{a_{19}}{a_0} M_{19} = M_{19} \sqrt{\frac{T_{19}}{T_0}} \tag{4.40}$$

$$\frac{F_c}{\dot{m}_c} = \frac{a_0}{g_c}\left[(1+f)\frac{V_9}{a_0} - M_0 + (1+f)\frac{R_{itb}}{R_c}\frac{T_9/T_0}{V_9/a_0}\left(1-\frac{P_0}{P_9}\right)\frac{1}{\gamma_c}\right] \tag{4.41}$$

$$\frac{F_f}{\dot{m}_f} = \frac{a_0}{g_c}\left(\frac{V_{19}}{a_0} - M_0 + \frac{T_{19}/T_0}{V_{19}/a_0}\frac{1-P_0/P_{19}}{\gamma_c}\right) \tag{4.42}$$

$$\frac{F}{\dot{m}_0} = \frac{\dfrac{F_c}{\dot{m}_c} + \alpha\dfrac{F_f}{\dot{m}_f}}{(1+\alpha)} \tag{4.43}$$

$$S = \frac{f_b + f_{itb}}{(1+\alpha)\dfrac{F}{\dot{m}_0}}$$

(4.44)

$$\frac{\dot{W}_{out}}{\dot{m}_c} = \frac{1}{2 \cdot g_c}\left\{(1+f)\cdot V_9^2 - V_0^2 + \alpha \cdot \left(V_{19}^2 - V_0^2\right)\right\}$$

(4.45)

$$\frac{\dot{Q}_{in}}{\dot{m}_c} = f_b \cdot h_{PR-b} \cdot \eta_b + f_{itb} \cdot h_{PR-ITB} \cdot \eta_{ITB}$$

(4.46)

$$\eta_{TH} = \frac{\dot{W}_{out}/\dot{m}_c}{\dot{Q}_{in}/\dot{m}_c}$$

(4.47)

$$\eta_P = \frac{F/\dot{m}_0\,(1+\alpha)V_0}{\dot{W}_{out}/\dot{m}_c}$$

(4.48)

$$\eta_O = \eta_{TH} \cdot \eta_P$$

(4.49)

5. User's Manual
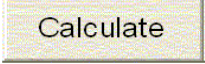
The Microsoft® Excel program is written in combination between spreadsheet neuron cells, visual basic, and macrocode. These three combinations provide user-friendly software that compilation and preprocessing are no longer necessary. The input is to well-labeled Microsoft® Excel cells. Most of the values are pre-specified and an example case is displayed. It is good practice to save this case by another name before modifying the spread sheet in order to retrieve the starting case. User obtains result plots right a way just by clicking some simple buttons.

5.1 Definitions

First of all, it is necessary for users to understand some icons that appear in the Microsoft® Excel sheets, for example, the *Input* sheet as shown in figure 5.1. Table 5.1 shown below lists down all the icons along with their descriptions.

Table 5.1.—Different kinds of tools and indicators

Name	Appearance (for example)	Descriptions
Combo box	**ITB** ON ▼	Users change options through selecting the items in the pull down menu list.
Button	Calculate	Clicking any button will execute the macrocode associated with it.
User input		This is where users input the values for variables.
Indicator 1		The values here change with altitude. Do not modify.
Indicator 2		All input values are read and shown here. Do not modify.

5.2 Program Outline

The program mainly comprises seven types of sheets, namely *CoverPage*, *Instructions*, *Input*, plot sheets, data sheets, *Singlept* and *Station*. Meanwhile, the main code structure is shown in figure B.1 in appendix B.

5.2.1 CoverPage.—The *CoverPage* sheet contains the information of authors of this program. Any questions regarding the program can be addressed to us through email or by phone.

5.2.2 Instructions.—First time users are strongly recommended to read this sheet before running the program. Since there are always possibilities of getting error computations such as division by zero, square root of a negative quantity, or over floating and under floating number, the program is written such that it will not crash if those errors are encountered during the computation. It will instead tell the user where the computation encounters those errors. In this sheet, you will find details of how to run the program and how to fix a problem if something goes wrong.

This sheet also explains several assumptions made in the equations so that the users aware of some cases in the equations that have been idealized to simplify the problems.

5.2.3 Input.—This sheet is where most of the inputs are specified. The program will check input values in this sheet to make sure that all the inputs are specified. It will tell the users if there are inputs that have not been specified.

There are four Combo Box in the *Input* sheet (*Combo Box* is a list box that displays a list of values and lets the users select one of the value in the list), namely ***ITB***, ***Unit***, ***Fuel Burn Model*** and ***Choose a Plot***, as shown in figure 5.1. You need first to specify the option in these combo boxes, such as ***ITB***, ***Unit*** and ***Fuel Burn Model***, before moving on to combo box ***Choose a Plot***.

Combo Box ***Unit*** lets you specify the unit system. Currently, the program can handle two unit systems, i.e., British gravitational units (**English**) and International system of units (**SI**).

Combo Box ***ITB*** lets you turn **ON** and **OFF** the Inter-stage Turbine Burner (*ITB*). This feature provides a flexibility to choose two types of engine and they are engine with ITB-ON and engine with ITB-OFF. With this feature, you will be able to see how the engine performance behaves with ITB-ON and with ITB-OFF.

Combo Box ***Fuel Burn Model*** let user choose two models for the computation of the fuel-air-ratio inside the burner, i.e., *Constant Specific Heat* (*CSH*) model and the *Modified Specific Heat* (*MSH*) model [3, 4].

Figure 5.1—*Input* sheet

Once all the input values and the options in combo box ***ITB***, ***Unit***, and ***Fuel Burn Model*** are specified, you can specify an option in combo box ***Choose a Plot***. This combo box provides several options to choose from, and they are:

1. Vs Compressor Pressure Ratio
2. Vs Flight Condition Mach Number
3. Vs Fan Pressure Ratio
4. Vs ByPass Ratio
5. Vs Main Burner Exit Temperature

In each option, it performs multiple calculations at different values of only one corresponding design variable. Once you select one of them, you will be directed to the relevant plot sheet.

5.2.4 plot sheets.—Please refer to section **5.3 Multi-point Calculations** for detailed information.

5.2.5 data sheets.—Please refer to section **5.3 Multi-point Calculations** for detailed information.

5.2.6 Singlept.—Please refer to section **5.4 Single-point Calculation** for detailed information.

5.2.7 Station.—Please refer to section **5.5 Engine Station** for detailed information.

5.3 Multiple-Point Calculations

The following discussion describes the instructions on how to run the program for each option available in combo box ***Choose a Plot*** in *Input* sheet. Each option shares the similar code structure as shown in figure B.2 in appendix B.

5.3.1 "Vs Compressor Pressure Ratio".—When this option is chosen, users will be directed to a plot sheet, namely *ST_VS_PIc*, as shown in figure 5.2. This sheet is used to plot engine performances (e.g., *specific thrust* or *thrust specific fuel consumption*) and other properties (e.g., overall efficiency, nozzle jet velocity ratios, overall efficiency, fuel-air ratio, *ITB* inlet velocity and temperature rise across *ITB*) versus *compressor pressure ratio* (π_c) with different bypass ratio. In order to execute the code properly, users are required to follow those circled number 1 through 3 sequentially as shown in figure 5.2.

First of all, user needs to specify the values for three input parameters (i.e., π_{cL}, π_f, and M_0) as well as the lower and upper bound limit for "*Compressor pressure ratio*" (π_c) and the increment ($\Delta\pi_c$) (see fig. 5.3). For instance, the lower and upper bound limit are 12 and 50, respectively, whereas the increment is 1.
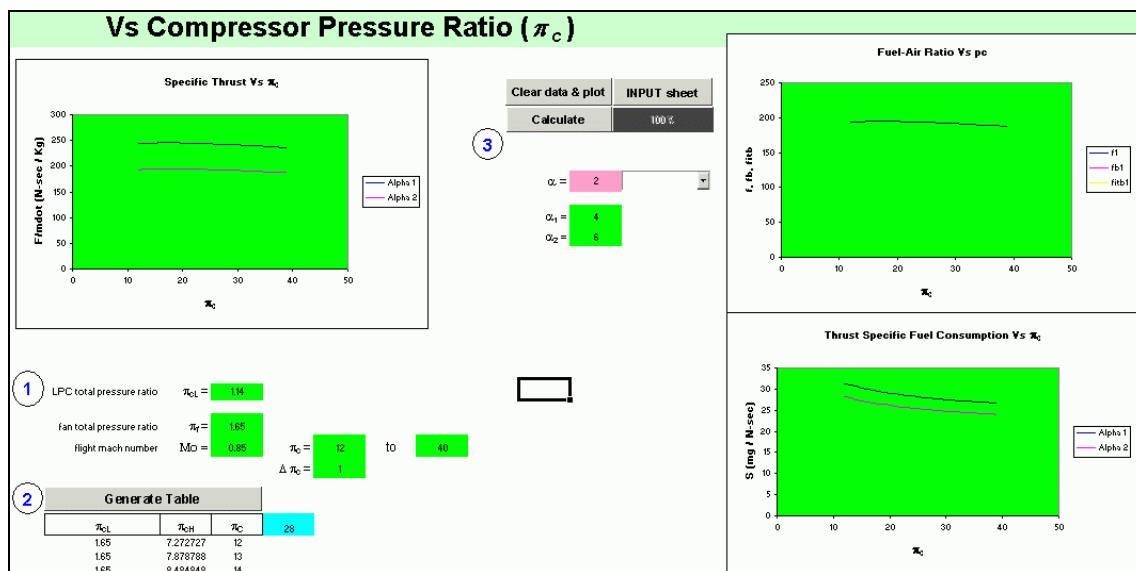

Figure 5.2.—"Vs Compressor Pressure Ratio" plot sheet

What follows is to compute the values for *HP*-compressor pressure ratio (π_{cH}). By clicking the '***Generate***' button, a tabular data for the compressor (including π_{cL}, π_{cH}, and π_c) will be listed as shown in figure 5.4. The cyan cell to the right of π_c indicates the total number of iteration for π_c. The smaller the value for $\Delta\pi_c$, the larger the total number of π_c; and, therefore, more calculation at different values of π_c.

Thirdly, users are free to choose the number of bypass ratio (α) by selecting options from the pull down menu as shown in figure 5.5. If it is more than 3 bypass ratios, users are required to manually input any number greater than 3 by selecting '**User-Defined**' option.

At this point, users are ready to run the code and generate the plots, simply by clicking '***Calculate***' button. All computed data will be tabulated in seven separate data sheets, namely, *DataSTPIc*, *DataSFPIc*, *OverallPIc*, *NVCorePIc*, *NVFanPIc*, *VitbPIc*, and *dTrisePIc*.

Users are advised not to modify or change values in any of these data sheets. Clearing data as well as plots can be done by clicking 'Clear data & plot' button (see fig. 5.5).

To return to Input sheet for other runs with different design parameters, users simply click on '*Input sheet*' button next to '*Calculate*' button.

Figure 5.3.—Input parameters in "Vs Compressor Pressure Ratio" plot sheet

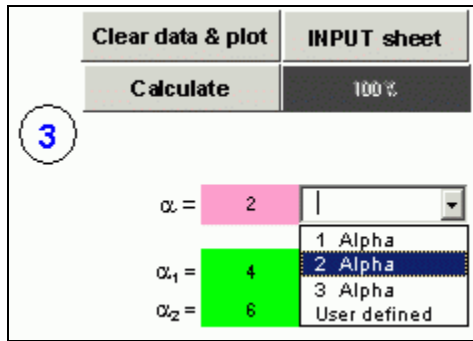Figure 5.4.—Tabular data for the compressor pressure ratios

Figure 5.5.—Pull-down menu for
fan bypass ratios (α)

5.3.2 "Vs Flight Condition Mach Number".—When users choose this option, the program hides the plot sheets and data sheets from the previous use and shows a associated plot sheet (i.e., *ST_VS_Mo*) and seven associated data sheets (i.e., *DataSTMo*, *DataSFMo*, *OverallMo*, *NVCoreMo*, *NVFanMo*, *VitbMo*, and *dTriseMo*.) Users will then be directed from *Input* sheet to *ST_VS_Mo* sheet in a second. Similarly, this sheet is used to plot engine performances (e.g., *specific thrust* or *thrust specific fuel consumption*) and other properties (e.g., overall efficiency, nozzle jet velocity ratios, overall efficiency, fuel-air ratio, *ITB* inlet velocity and temperature rise across *ITB*) versus *flight Mach number* (M_0) with different bypass ratio.

Similar to the instructions for compressor pressure ratio, user first needs to specify the values for three input parameters (i.e., π_{cL}, π_f, and π_c) as well as the range of M_0 and the increment (ΔM_0).

Secondly, users are free to choose the number of bypass ratio (α) by selecting options from the pull down menu. At this point, users are ready to run the code and generate the plots, by simply clicking '**Calculate**' button. All computed data will be tabulated in all seven separate sheets just mentioned above.

5.3.3 "Vs Fan Pressure Ratio".—Similar to flight Mach number, this option opens a plot sheet (i.e., *ST_VS_PIf*) and seven data sheets (i.e., *DataSTPIf*, *DataSFPIf*, *OverallPIf*, *NVCorePIf*, *NVFanPIf*, *VitbPIf*, and *dTrisePIf)*. It plots engine performances (e.g., *specific thrust* or *thrust specific fuel consumption*) and other variables (e.g., overall efficiency, nozzle jet velocity ratios, overall efficiency, *ITB* inlet velocity and temperature rise across *ITB*) versus fan pressure ratio (π_f) with different bypass ratio. The instructions to run the program in this sheet are similar to those for 'flight Condition Mach number'. (See section 5.3.2.)

5.3.4 "Vs ByPass Ratio".—This option opens a plot sheet (i.e., *ST_VS_Alp*) and seven data sheets (i.e., *DataSTAlp*, *DataSFAlp*, *OverallAlp*, *NVCoreAlp*, *NVFanAlp*, *VitbAlp*, and *dTriseAlp)*. It plots engine performances (e.g., *specific thrust* or *thrust specific fuel consumption*) and other variables (e.g., overall efficiency, nozzle jet velocity ratios, overall efficiency, *ITB* inlet velocity and temperature rise across *ITB*) versus different *bypass ratio* (α) with different fan total pressure ratios. The instructions to run the program in this sheet are analogous to those described above. The only difference is that selection of α is replaced by π_f.

5.3.5 "Vs Main Burner Exit Temperature".—This option opens a plot sheet (i.e., *ST_VS_Tt4*) and seven data sheets (i.e., *DataSTt4*, *DataSFTt4*, *OverallTt4*, *NVCoreTt4*, *NVFanTt4*, *VitbTt4*, and *dTriseTt4)*. It plots engine performances (e.g., *specific thrust* or *thrust specific fuel consumption*) and other variables (e.g., overall efficiency, nozzle jet velocity ratios, overall efficiency, *ITB* inlet velocity and temperature rise across *ITB*) versus *main burn exit temperature* (T_{t4}) with different flight Mach number. The instructions to run the program in this sheet are similar to those for 'flight Condition Mach number'. (See section 5.3.2.)

5.3.5 Summary.—In summary, you need to do the followings to run the program:

1. Go to the *Input* sheet
2. Specify the ***Unit*** system (SI or English)
3. Specify the ***ITB* switch**. Is the computation for engine with ITB-ON or for engine with ITB-OFF?
4. Specify the ***Fuel Burn Model*** system (CSH or MSH)
5. Enter all the input parameters indicated in green cells (do not modify or change the value indicated in cyan).
6. Specify ***Choose a Plot***. You will be directed to a new sheet depending on the selection.

In sheet ***ST_VS_PIc*** (Compressor Pressure Ratio),

   a. Specify number of bypass ratio (α).
   b. Specify all input parameters in green cells.
   c. Click '***Generate***' to generate high-pressure compressor total pressure ratio.
   d. Click '***Calculate***' to compute and plot the results.
   e. Repeat the above steps for different input parameters. To return to *Input* sheet, simply click '***Input sheet***' button.

In sheet ***ST_VS_Mo*** (Flight Condition Mach Number),

   a. Specify number of bypass ratio (α).
   b. Specify all input parameters in green cells.
   c. Click '***Calculate***'.
   d. Repeat the above steps for different input parameters. To return to *Input* sheet, simply click '***INPUT sheet***' button.

In sheet ***ST_VS_PIf*** (Fan Pressure Ratio),

   a. Specify number of bypass ratio (***α***).
   b. Specify all input parameters in green cells.
   c. Click '***Calculate***' to compute and plot the results.
   d. Repeat the above steps for different input parameters. To return to *Input* sheet, simply click '***Input sheet***' button.

In sheet ***ST_VS_Alp*** (ByPass Ratio),

   a. Specify number of fan total pressure ratio ($\boldsymbol{\pi_f}$).
   b. Specify all input parameters in green cells.
   c. Click '***Calculate***'.
   d. Repeat the above steps for different input parameters. To return to *Input* sheet, simply click '***INPUT sheet***' button.

In sheet ***ST_VS_Tt4*** (Main Burner Exit Temperature),

   a. Specify number of flight Mach number ($\boldsymbol{M_0}$).
   b. Specify all input parameters in green cells.
   c. Click '***Calculate***'.
   d. Repeat the above steps for different input parameters. To return to *Input* sheet, simply click '***INPUT sheet***' button.

5.4 Single Point Calculation

All instructions described above are termed as the *multi-point calculations* at different values of only one design parameter (e.g., π_c, π_f, M_0, α, or T_{t4}) The computed results show how the performance of a family of engines was determined by engine design choices and flight Mach number.

Once the most promising engine is selected by users (i.e., all engine components are fixed, e.g., π_c, π_f, altitude, α etc.), single point calculation is then run to get the engine performance at this particular operating conditions. These output data represents the selected engine's design point condition. In order to predict the engine performance at off-design conditions, these outputs are then used as the reference conditions in an off-design code. This step is important because different reference conditions (i.e., different engines) will give different performance over the whole flight spectrum.

For user's reference, the flow chart of this computation is shown in figure B.3 in appendix B.

5.4.1 Exporting Reference Engine Data.—For convenience, authors include **'Input/Output files'** feature in this code. The output data from this on-design code can be exported to be a reference engine data file, which is required in off-design calculation. As a result, users do not need to manually re-input the reference conditions in off-design code, which is a time-consuming process.

Users are to follow the step 1 to 13 to generate a reference engine data file:

1. Select *Input* sheet (as shown in fig. 5.1).
2. Input the engine characteristics in *Input* sheet.
3. Select *SinglePt* sheet (as shown in fig. 5.6).
4. Input values of independent variables (i.e., M_0, α, altitude, π_c and throttle settings) in green cells.
5. Click on '***Perform calculation***' button to calculate the selected engine performance at a design point.
6. Both the input values from *Input* sheet and the solution will be shown in light-blue cells.
7. Click on '***Export reference engine data***' button to export these reference engine data to a text file.
8. Figure 5.7 will appear and request for specifying the path and filename.
9. Users may need to enter a new path if necessary, for example, "*c:\itb\reference.txt*". The default path and filename is "c:*\reference.txt*". Figure 5.8 appears when one of these situations happens:
   (i) The specified directory (default drive is 'c:\') does not exist.
   (ii) The file is being used by another program.
10. Check for existing drive path or/and specify another filename. (Restart from step 3 again).
11. All reference data and engine characteristics of a specific design-point engine are successfully exported.
12. Repeat step 1 to 11 for different engines.

On-design Single Point Calculation

Input check:

$P_0/P_{10} =$ 1
$P_0/P_{19} =$ 1

$\pi_{d\,max} =$ 0.99
$\pi_b =$ 0.95
$\pi_{ITB} =$ 0.95
$\pi_n =$ 0.99
$\pi_{nf} =$ 0.98

$e_{cH} =$ 0.9085
$e_{cL} =$ 0.8738
$e_{tH} =$ 0.8999
$e_{tL} =$ 0.9204
$e_T =$ 0.93

$\eta_b =$ 0.99
$\eta_{ITB} =$ 0.99
$\eta_{m-HP} =$ 0.92
$\eta_{m-LP} =$ 0.93
$h_{PR-b} =$ 43124 kJ/kg
$h_{PR-nb} =$ 43124 kJ/kg

$C_{pc} =$ 1.001994 kJ/kg-K
$C_{pt} =$ 1.270719 kJ/kg-K
$C_{p/tb} =$ 1.20289 kJ/kg-K
$\gamma_c =$ 1.401343
$\gamma_t =$ 1.291711
$\gamma_{nb} =$ 1.313314

$T_0 =$ 216.65 K

Input Design variables:

$M_0 =$ 0
$\alpha =$ 8.4
$\pi_{cL} =$ 1.3
$\pi_c =$ 39.3
$\pi_f =$ 1.3
$T_{t4} =$ 1600.0 K
$T_{t4.5} =$ 1300.0 K
$T_{t4.5-ITBon} =$ 1300.0 K

$h =$ 0 km
$T_0 =$ 288.15 K
$P_0 =$ 101325.00 Pa

| Perform calculation | INPUT sheet |

| Export reference engine data |

Outputs:

$\pi_{tH} =$ 0.152272
$\pi_{tL} =$ 0.467057
$\pi_{cH} =$ 30.23077
$\pi_{cL} =$ 1.3
$\pi_T =$ 1.3
$\tau_{tH} =$ 0.68216
$\tau_{tL} =$ 0.84606
$\tau_{cH} =$ 2.928886
$\tau_{cL} =$ 1.089799
$\tau_T =$ 1.08415
fuel model = **MSH**
$f_b =$ 0.020891
$f_{ITB} =$ 0.006565

$M_8 =$ 1
$M_{18} =$ 0.585351
$\alpha =$ 8.4
F/mdot = 254.2952 (N-sec / Kg)
$S =$ 11.48572 (mg / N-sec)
$\eta_P =$ 1.878652 %
$\eta_{TH} =$ 36.95226 %
$\eta_O =$ 0.694204 %

$\eta_{tH} =$ 0.917937314
$\eta_{tL} =$ 0.926882611
$\eta_{cH} =$ 0.857801144
$\eta_{cL} =$ 0.869008139
$\eta_T =$ 0.92733971

$P_{t19}/P_{19} =$ 1.261348375
$T_{t19}/T_0 =$ 1.084172154
$V_{19}/V_0 =$ 58.95568433
$V_9/V_0 =$ 210.5988768
$T_9/T_0 =$ 3.075658578
$P_9/P_9 =$ 2.472460107

$M_9 =$ 1.240438015
$M_{t9} =$ 0.585350632

Remarks:

=> Input values here.
=> Do not modify. Solutions shown here.
=> Do not modify.

Figure 5.6.—On-design single point calculation sheet.

ITB cycle analysis

Enter the path and filename (that is not used by another program)

| OK | Cancel |

h:\reference.txt

Figure 5.7.—Dialog box for specifying the path and filename where the reference conditions data will be stored.
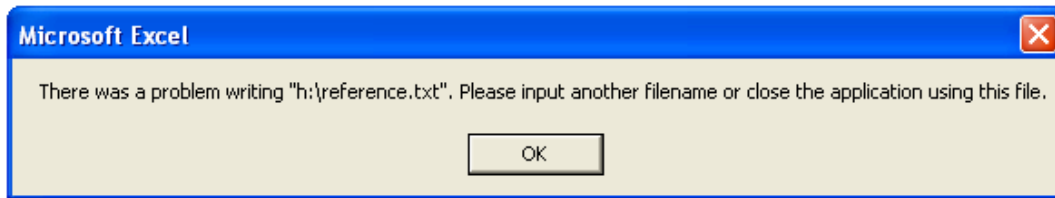
Figure 5.8.—This dialog box appears when there is an error
writing reference conditions data to a specified file.

Figure 5.9.—Engine station data sheet

5.5 Engine Station Data

The last sheet in the program is the *Station* sheet. This sheet displays the engine station flow properties (i.e., temperature and pressure) in forms of a table (see fig. 5.9) and charts (see fig. 5.10) based on the user input Mach number data at certain stations.

Most of the input parameters are from the *Input* sheet. Additional inputs are also needed, such as those listed in "Inputs" column (i.e., to the left of the engine station data table) and Mach numbers at some engine stations (as shown in fig. 5.9). To click the '*Update Station Data*' button will update the flow properties at each engine station. Please refer to figure B.4 in appendix B for the code structure of this sheet.
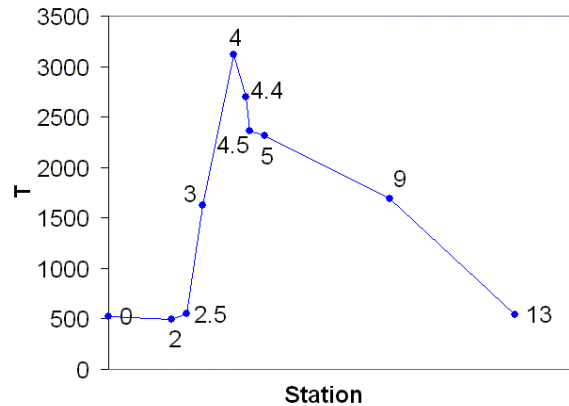
(a) Temperature
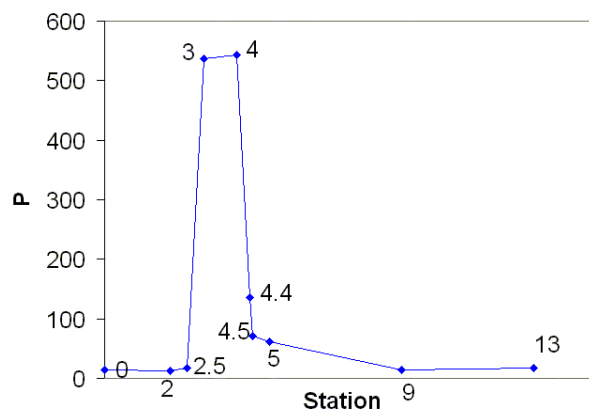
(b) Pressure

Figure 5.10.—Examples of pressure and temperature vs engine stations

5.6 Discussions

A typical value for local Mach number at the *ITB* entrance is selected to be 0.3. This value ($M_{4.4} = 0.3$) is then used to compute *ITB* inlet velocity ($v_{4.4}$), on which one of the factors *ITB* design was based. In fact, each plot sheet will show the change of *ITB* inlet velocity with the corresponding design parameter, for example, $v_{4.4}$ versus M_0 in *ST_VS_Mo* sheet.

At ITB-OFF condition, a plot of "*Temperature Rise across ITB*" in each plot sheet (e.g., *ST_VS_PIc*, *ST_VS_Mo*, *ST_VS_PIf*, and *ST_VS_Alp*) will be cleared out. It is because the ITB-OFF engine acts as if it is a turbofan engine without any increase across *ITB*.

5.7 Troubleshooting

This program has been debugged several times. Therefore, whenever you encounter computation errors due to either zero division or square root of a negative quantity, you will be notified by a pop up window indicating where the computation problem is. It will tell you on which equation that the computational error is encountered. If you have any comments or bug problems you encounter in the program, you can report them to us for further improvement. Details about the contact number can be found in the *CoverPage* sheet of the program.
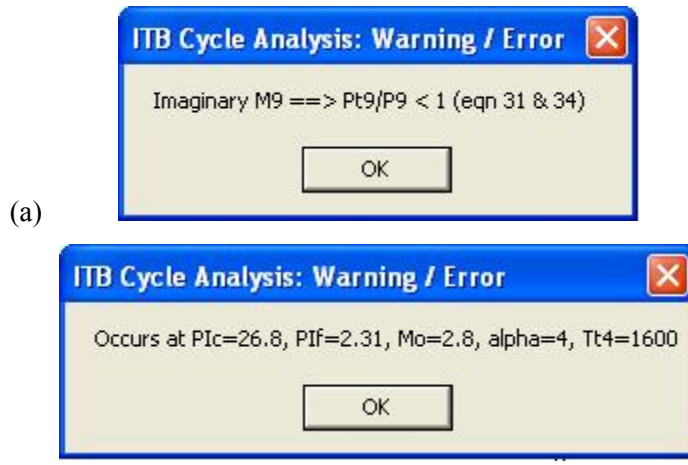
Figure 5.11.—Pop-up windows showing warning or error messages:
(a) Equations where the error occurs; (b) The current values of
design variables while error is encountered.

5.7.1 Out of Range.—In multiple-point calculation, users may always see these pop-up windows as shown in figures 5.11a and 5.11b. There are two possibilities of having this error or warning messages:

(i) The input values are incorrect. For instance, the main burner exit temperature (T_{t4}) may be too small for an engine to produce enough thrust. Please double check all input values and try again.

(ii) During the multiple-point computation, the design variable may be out of range. It will happen, especially for these design variables such as flight Mach number, fan pressure ratio and bypass ratio. For instance, the specific thrust of an engine is approaching zero as the flight Mach number is 3. If the upper limit of flight Mach number is set to be greater than 3 (e.g., 5), the code will not be able to proceed at Mach number higher than 3 and thus give these warning messages.

5.7.2 Plotting errors.—It is also predicted that the plotting macro can encounter some problems in the future if the users do not fully understand the program. Therefore, authors have set up a way in order to fix the problem. In case the plot starts giving problem, you need to do the followings (this apply to all plot sheets: *ST_VS_PIc*, *ST_VS_Mo*, *ST_VS_PIf*, *ST_VS_Alp, and ST_VS_T*$_{t4}$):

a. Go to the plot sheet (e.g., *ST_VS_Mo*)
b. Go to cell **D5**
c. Note that you will not be able to click on that cell because it is lying on the back of the plot chart. You may want to use arrow button from your keyboard in order to move to cell **D5**.
d. In that cell, you will see "SUCCESS". Change the character to "FAIL".
e. Clear the series in the chart plot by clicking right mouse button (RMB)on the chart plot.
f. In RMB menu list, choose *Source Data*
g. In 'Source Data' windows, pick *Series* tab and remove all the series.

Users are not expected to understand macro code in the program. However the part that takes care the computation can be found in *Module1 Sub Itb*( ). To open Microsoft® Excel Visual Basic windows, users need to press **Alt + F11**. Any modification can be made in subroutine *Itb*( ). **Do not add new variables into the program!**

Appendix A—Macro Visual Basic Code

```
Sub itb()
  Dim rc, rb, rt, a0, v0, eta_r, tau_alp_b, tau_alp_itb
  Dim tau_c, tau_b, tau_itb
  Dim T19_T0, fc_mc, ff_mf, denu, nume, v19, v9
  '
  Style = vbYes
  Style1 = vbYes
' Msg = "Do you want to jump to the next alpha?"
  Msg1 = "Division by zero ==> Check zero inputs for gama's (eqn 1,2,3)"
  Msg2 = "Imaginary sound speed ==> Check negative inputs for gamac, gc or T0 (eqn 4)"
  Msg3 = "Division by zero ==> gamac cannot = 1 (eqn 7)"
  Msg4 = "Division by zero ==> Check zero inputs for cpc, T0, ecH, ecL & ef (eqn 10, 11, 12, 13 & 14)"
  Msg5 = "Division by zero ==> Check zero inputs for tau_r & tau_c (eqn 16)"
  Msg6 = "Division by zero ==> tau_cH, tau_cL & tau_f cannot =1 (eqn 17, 18, 19)"
  Msg7 = "Invalid (negative) tau_tH ==> Refer to equation 21"
  Msg8 = "Imaginary M9 ==> Pt9/P9 < 1 (eqn 31 & 34)"
  Msg9 = "Imaginary M19 ==> Pt19/P19 < 1 (eqn 36 & 37)"
  Msg10 = "Division by zero => denominator of 'fb' eqn cannot =0 (eqn 20)"
  Msg11 = "Division by zero => denominator of 'fitb' eqn cannot =0 (eqn 22)"
  wdata = 1
  fbi = 0
  fitbi = 0
  'warn = 0
  '
  'If gamac = 0# Or gamat = 0# Or gamaitb = 0# Then
    'response = MsgBox(Msg1, style, Title)
    'Msg1 = "Occurs at " & "PIc=" & pi_cH * pi_cL & ", PIf=" & pi_f & ", Mo=" & M0 & ", alpha=" & alpha
    'response = MsgBox(Msg1, Style, Title)
    'If singlept <> 1 Then jump = MsgBox(Msgsheet, Style1, Title)
    'GoTo 10
  'End If
  '
  'added on 5/13/04 for controling ITB switch -1
  itbinit = 1
  If Sheets("Input").ComboBox2.Value = "OFF" Then itbinit = 0
  'added on 5/13/04 for controling ITB switch -2
'Constants
  Call enthalpy(1, T_o, 0, 0, Cpc, gamac)
  Call enthalpy(1, Tt4, 0, 0, Cpt, gamat)
  rc = (gamac - 1#) * Cpc / gamac   '(1)
  rt = (gamat - 1#) * Cpt / gamat   '(2)
  '
  If gamac < 0# Or rc < 0# Or T_o < 0# Or gc < 0# Then
    response = MsgBox(Msg2, Style, Title)
    'Msg2 = "Occurs at " & "PIc,PIf,Mo,ByPass = " & pi_cH * pi_cL & "," & pi_f & "," & M0 & "," & alpha
    'Msg2 = "Occurs at " & "PIc=" & pi_cH * pi_cL & ", PIf=" & pi_f & ", Mo=" & M0 & ", alpha=" & alpha &
", Tt4=" & Tt4
    'response = MsgBox(Msg2, Style, Title)
    'warn = 1
    'If singlept <> 1 Or last = 0 Then jump = MsgBox(Msgsheet, Style1, Title)
    GoTo 10
  End If
  a0 = (gamac * rc * T_o * gc) ^ 0.5   '(4)
```

```
    v0 = a0 * M0                    '(5)
'
    If gamac = 1# Then
     response = MsgBox(Msg3, Style, Title)
     'Msg3 = "Occurs at " & "PIc=" & pi_cH * pi_cL & ", PIf=" & pi_f & ", Mo=" & M0 & ", alpha=" & alpha &
", Tt4=" & Tt4
     'response = MsgBox(Msg3, Style, Title)
     'warn = 1
     'If singlept <> 1 Then jump = MsgBox(Msgsheet, Style1, Title)
      GoTo 10
    End If
'
    tau_r = (gamac - 1#) * (0.5 * M0 ^ 2) + 1#   '(6)
    pi_r = tau_r ^ (gamac / (gamac - 1))         '(7)
'
    If M0 <= 1# Then                    '(8)
     eta_r = 1#
    End If
    If M0 > 1 And M0 <= 5 Then
     eta_r = 1# - 0.075 * (M0 - 1#) ^ 1.35
    End If
    If M0 > 5 Then
     eta_r = 800# / (935# + M0 ^ 4)
    End If
    pi_d = pi_dmax * eta_r              '(9)
'
    If pi_cL < pi_f Then pi_cL = pi_f
    pi_cH = pi_c / pi_cL
'
    If Cpc = 0# Or T_o = 0# Or gamac = 0# Or e_cH = 0# Or e_cL = 0# Or e_f = 0# Then
     response = MsgBox(Msg4, Style, Title)
     'Msg4 = "Occurs at " & "PIc=" & pi_cH * pi_cL & ", PIf=" & pi_f & ", Mo=" & M0 & ", alpha=" & alpha &
", Tt4=" & Tt4
     'response = MsgBox(Msg4, Style, Title)
     'If singlept <> 1 Then jump = MsgBox(Msgsheet, Style1, Title)
     'warn = 1
      GoTo 10
    End If
   24
    tau_alp_b = Cpt * Tt4 / (Cpc * T_o)          '(10)
    tau_cH = pi_cH ^ ((gamac - 1#) / (gamac * e_cH))     '(12)
    tau_cL = pi_cL ^ ((gamac - 1#) / (gamac * e_cL))     '(13)
    tau_f = pi_f ^ ((gamac - 1#) / (gamac * e_f))        '(14)
    tau_c = tau_cH * tau_cL                  '(15)
'
    If tau_r = 0# Or tau_c = 0# Then
     response = MsgBox(Msg5, Style, Title)
     'Msg5 = "Occurs at " & "PIc=" & pi_cH * pi_cL & ", PIf=" & pi_f & ", Mo=" & M0 & ", alpha=" & alpha &
", Tt4=" & Tt4
     'response = MsgBox(Msg5, Style, Title)
     'warn = 1
     'If singlept <> 1 Then jump = MsgBox(Msgsheet, Style1, Title)
      GoTo 10
    End If
    tau_b = Tt4 / (T_o * tau_r * tau_c)          '(16)
'
```

```
    If tau_cH = 1# Or tau_cL = 1# Or tau_f = 1# Then
      response = MsgBox(Msg6, Style, Title)
      'Msg6 = "Occurs at " & "PIc=" & pi_cH * pi_cL & ", PIf=" & pi_f & ", Mo=" & M0 & ", alpha=" & alpha &
", Tt4=" & Tt4
      'response = MsgBox(Msg6, Style, Title)
      'warn = 1
      'If singlept <> 1 Then jump = MsgBox(Msgsheet, Style1, Title)
      GoTo 10
    End If
    eta_cH = ((tau_cH ^ e_cH) - 1#) / (tau_cH - 1#)      '(17)
    eta_cL = ((tau_cL ^ e_cL) - 1#) / (tau_cL - 1#)      '(18)
    eta_f = ((tau_f ^ e_f) - 1#) / (tau_f - 1#)          '(19)
    '
   'add MSH on 7/30/04 -1
   'Component: MAIN BURNER
    h_0 = Cpc * T_o
    temp_fb = eta_b * hPRb / h_0 - tau_alp_b
    If temp_fb = 0# Then
      response = MsgBox(Msg10, Style, Title)
      'Msg7 = "Occurs at " & "PIc=" & pi_cH * pi_cL & ", PIf=" & pi_f & ", Mo=" & M0 & ", alpha=" & alpha &
", Tt4=" & Tt4
      'response = MsgBox(Msg7, Style, Title)
      'If singlept <> 1 Then jump = MsgBox(Msgsheet, Style1, Title)
      'warn = 1
      GoTo 10
    End If
   'Fuel model 1: CSH
    If Sheets("Input").ComboBox4.Value = "CSH" Then
      fb = (tau_alp_b - tau_r * tau_c) / temp_fb        '(20a)
    Else
   'Fuel model 2: MSH
      loop3 = 0
      Tt3 = T_o * tau_r * tau_c                      'eqn(20b)
      Call enthalpy(0, Tt3, 0, h_t3, 0, 0)
      f_4i = (tau_alp_b - tau_r * tau_c) / temp_fb     'eqn(20c),initial value for f_4i
   3
      If loop3 > 20 Then
        GoTo 10
      End If
      Call enthalpy(0, Tt4, f_4i, h_t4, 0, 0)
      temp_fb = eta_b * hPRb - h_t4
      If temp_fb = 0# Then
        response = MsgBox(Msg10, Style, Title)
        'Msg7 = "Occurs at " & "PIc=" & pi_cH * pi_cL & ", PIf=" & pi_f & ", Mo=" & M0 & ", alpha=" & alpha
& ", Tt4=" & Tt4
        'response = MsgBox(Msg7, Style, Title)
        'If singlept <> 1 Then jump = MsgBox(Msg_jump, Style1, Title)
        'warn = 1
        GoTo 10
      End If
      fb = (h_t4 - h_t3) / temp_fb                    'eqn(20d)
      If Abs(fb - f_4i) > 0.0001 Then
        f_4i = fb
        loop3 = loop3 + 1
        GoTo 3
      End If
```

```vb
        End If
      'lkh1 - added cp=cp(T,f) and gama=gama(T,f) on 11/15/04
      Err_fb = Abs(fbi - fb)
      If Err_fb > 0.0001 Then
        fbi = fb
        Call enthalpy(1, Tt4, fb, 0, Cpt, gamat)
        GoTo 24
      End If
      'lkh2
      'add MSH on 7/30/04 -2
      '
      tau_tH = 1# - (tau_cH - 1#) * tau_cL * tau_r / ((1# + fb) * tau_alp_b * effm_tH) '5/11/04
                                    '(21)
      If tau_tH < 0# Then
          response = MsgBox(Msg7, Style, Title)
          'Msg7 = "Occurs at " & "PIc=" & pi_cH * pi_cL & ", PIf=" & pi_f & ", Mo=" & M0 & ", alpha=" & alpha
& ", Tt4=" & Tt4
          'response = MsgBox(Msg7, Style, Title)
          Cells(22, 4).Select
          Msg7 = "The Tt4 lower limit (as indicated) is too low to converge, increase Tt4 lower limit and try again!"
          response = MsgBox(Msg7, Style, Title)
          'warn = 1
          GoTo 10
      End If

      If itbinit = 0 Then
        Tt4p5 = Tt4 * tau_tH
        Call enthalpy(1, Tt4p5, 0, 0, Cpitb, gamaitb)
        tau_alp_itb = Cpitb * Tt4p5 / (Cpc * T_o)        '(11)
        fitb = 0#
        tau_itb = 1#
        GoTo 5
      End If
      Call enthalpy(1, Tt4p5, 0, 0, Cpitb, gamaitb)
    25
      tau_alp_itb = Cpitb * Tt4p5 / (Cpc * T_o)
      If tau_alp_itb <= (tau_alp_b * tau_tH) Then
        itbinit = 0
        Tt4p5 = Tt4 * tau_tH
        Call enthalpy(1, Tt4p5, 0, 0, Cpitb, gamaitb)
        fitb = 0#
        tau_itb = 1#
        tau_alp_itb = Cpitb * Tt4p5 / (Cpc * T_o)
        GoTo 5
      End If
      '
      If itbinit = 1 Then
      'add MSH on 8/1/04 for ITB -1
      'Component: INTERSTAGE-TURBINE BURNER
        temp_fitb = eta_itb * hPRitb / h_0 - tau_alp_itb
        If temp_fitb = 0# Then
          response = MsgBox(Msg11, Style, Title)
          'Msg7 = "Occurs at " & "PIc=" & pi_cH * pi_cL & ", PIf=" & pi_f & ", Mo=" & M0 & ", alpha=" & alpha
& ", Tt4=" & Tt4
          'response = MsgBox(Msg7, Style, Title)
          'If singlept <> 1 Then jump = MsgBox(Msg_jump, Style1, Title)
```

```
        'warn = 1
          GoTo 10
      End If
    'Fuel model 1: CSH
      If Sheets("Input").ComboBox4.Value = "CSH" Then
        fitb = (tau_alp_itb - tau_alp_b * tau_tH) / (temp_fitb) * (1# + fb) '9/3/04
                                '(22a)
      Else
       'Fuel model 2: MSH
        loop4 = 0
        Tt4p4 = Tt4 * tau_tH                '(22b)
        Call enthalpy(0, Tt4p4, fb, h_t4p4, 0, 0)
        f_4p5i = (1# + fb) * (tau_alp_itb - tau_alp_b * tau_tH) / (temp_fitb)
                                '(22c),initial value for f_4p5i
    4
        If loop4 > 20 Then
          loop4 = 21
          GoTo 10
        End If
        Call enthalpy(0, Tt4p5, f_4p5i, h_t4p5, 0, 0)
        temp_fitb = eta_itb * hPRitb - h_t4p5
        If temp_fitb = 0# Then
          response = MsgBox(Msg11, Style, Title)
          'Msg7 = "Occurs at " & "PIc=" & pi_cH * pi_cL & ", PIf=" & pi_f & ", Mo=" & M0 & ", alpha=" &
alpha & ", Tt4=" & Tt4
          'response = MsgBox(Msg7, Style, Title)
          'warn = 1
          'If singlept <> 1 Then jump = MsgBox(Msg_jump, Style1, Title)
          GoTo 10
        End If
        fitb = (1# + fb) * (h_t4p5 - h_t4p4) / (temp_fitb) '(22d)
        If Abs(fb + fitb - f_4p5i) > 0.0001 Then
          f_4p5i = fb + fitb
          loop4 = loop4 + 1
          GoTo 4
        End If
      End If
    'lkh1 - added cp=cp(T,f) and gama=gama(T,f) on 11/15/04
      Err_fitb = Abs(fitbi - fitb)
      If Err_fitb > 0.0001 Then
        fitbi = fitb
        Call enthalpy(1, Tt4p5, fitb, 0, Cpitb, gamaitb)
        GoTo 25
      End If
    'lkh2
     'add MSH on 8/1/04 for ITB -2
      tau_itb = Tt4p5 / (T_o * tau_r * tau_c * tau_b * tau_tH) '(24)
     End If
    5
    ritb = (gamaitb - 1#) * Cpitb / gamaitb                '(3)
    f = fb + fitb                        '(23)
    tau_tL = 1# - (tau_cL - 1# + alpha * (tau_f - 1#)) * tau_r / ((1# + fb + fitb) * tau_alp_itb * effm_tL)

                                '(26)
    pi_tH = tau_tH ^ (gamat / ((gamat - 1#) * e_tH))        '(27)
    pi_tL = tau_tL ^ (gamaitb / ((gamaitb - 1#) * e_tL))      '(28)
```

```vba
    eta_tH = (1# - tau_tH) / (1# - tau_tH ^ (1# / e_tH))     '(29)
    eta_tL = (1# - tau_tL) / (1# - tau_tL ^ (1# / e_tL))     '(30)
'
    Pt9_P9 = P0_P9 * pi_r * pi_d * pi_cL * pi_cH * pi_b * pi_tH * pi_itb * pi_tL * pi_n
                                '(31)
    tempM9 = Pt9_P9 ^ ((gamaitb - 1#) / gamaitb)
    If tempM9 < 1# Then
        response = MsgBox(Msg8, Style, Title)
        'Msg8 = "Occurs at " & "PIc=" & pi_cH * pi_cL & ", PIf=" & pi_f & ", Mo=" & M0 & ", alpha=" & alpha
& ", Tt4=" & Tt4
        'response = MsgBox(Msg8, Style, Title)
        'warn = 1
        'If singlept <> 1 Then jump = MsgBox(Msgsheet, Style1, Title)
        GoTo 10
    End If
    Tt9_T0 = tau_r * tau_c * tau_b * tau_tH * tau_itb * tau_tL  '(32)
    T9_T0 = Tt9_T0 / Pt9_P9 ^ ((gamaitb - 1#) / gamaitb)      '(33)
'
    M9 = ((tempM9 - 1#) * 2# / (gamaitb - 1#)) ^ 0.5       '(34)'5/5/04
    M8 = M9
    If M9 >= 1 Then M8 = 1
    v9_a0 = M9 * (gamaitb * ritb * T9_T0 / (gamac * rc)) ^ 0.5  '(35)
    v9 = v9_a0 * a0
    v9_v0 = v9 / v0
'
    Pt19_P19 = P0_P19 * pi_r * pi_d * pi_f * pi_fn             '(36)
    tempM19 = Pt19_P19 ^ ((gamac - 1#) / gamac)
    If gamac < 1# Or tempM19 < 1# Then
        response = MsgBox(Msg9, Style, Title)
        'Msg8 = "Occurs at " & "PIc=" & pi_cH * pi_cL & ", PIf=" & pi_f & ", Mo=" & M0 & ", alpha=" & alpha
& ", Tt4=" & Tt4
        'response = MsgBox(Msg9, Style, Title)
        'warn = 1
        'If singlept <> 1 then jump = MsgBox(Msgsheet, Style1, Title)
        GoTo 10
    End If
    M19 = ((tempM19 - 1#) * 2# / (gamac - 1#)) ^ 0.5          '(37)
    M18 = M19
    If M19 >= 1 Then M18 = 1
    Tt19_T0 = tau_r * tau_f                                '(38)
    T19_T0 = Tt19_T0 / Pt19_P19 ^ ((gamac - 1#) / gamac)       '(39)
    v19_a0 = M19 * T19_T0 ^ 0.5                      '(40)
    v19 = v19_a0 * a0
    v19_v0 = v19 / v0
'
    fc_mc = (1# + f) * v9_a0 - M0 + (1# + f) * (ritb / rc) * (T9_T0 / v9_a0) * (1# - P0_P9) * (1# / gamac)
                                '(41)
    ff_mf = v19_a0 - M0 + (T19_T0 / v19_a0) * (1# - P0_P19) / gamac
                                '(42)
    F_mo = (a0 / gc) * (fc_mc + alpha * ff_mf) / (1# + alpha)   '(43)
'
    unitchange = 1#
    If Sheets("Input").ComboBox1.Value = "SI" Then
        unitchange = 1000000#
    Else
```

```
        unitchange = 3600#
      End If
      s = f / ((1# + alpha) * F_mo) * unitchange           '(44)
'(44)
      If F_mo < 0 Or s < 0 Then wdata = 0
      '
    'Efficiencies
      corenume = (1# + f) * v9 * v9 - v0 * v0 'corrected on 6/16/04
      fanume = alpha * (v19 * v19 - v0 * v0)
      nume = 0.5 / gc * (corenume + fanume)                '(45)
      denu = fb * hPRb * eta_b + fitb * hPRitb * eta_itb       '(46)
      '
      eta_thermal = nume / denu * 100#                  '(47)
      eta_P = (1# + alpha) * F_mo * v0 / nume * 100#          '(48)
      eta_O = (1# + alpha) * F_mo * v0 / denu * 100#          '(49)
      '
    'Mach = 0.3 at HP turbine exit
      M4p4 = 0.3
      Tt4p4 = tau_r * tau_c * tau_b * tau_tH * T_o
      T4p4 = Tt4p4 / (1# + 0.5 * (gamat - 1#) * M4p4 * M4p4)
      v4p4 = M4p4 * (gamat * rt * gc * T4p4) ^ 0.5
      dTitb = Tt4p4 * (tau_itb - 1#)
      GoTo 11
     10
      'If warn = 1 Then 'added on 11/30/04
        Msg = "Occurs at " & "PIc=" & pi_cH * pi_cL & ", PIf=" & pi_f & ", Mo=" & M0 & ", alpha=" & alpha & ",
Tt4=" & Tt4
        response = MsgBox(Msg, Style, Title)
        If last = 1 Then
          jump = 1
          GoTo 11
        End If
        If singlept <> 1 Then jump = MsgBox(Msgsheet, Style1, Title)
      ' End If
     11
End Sub
```

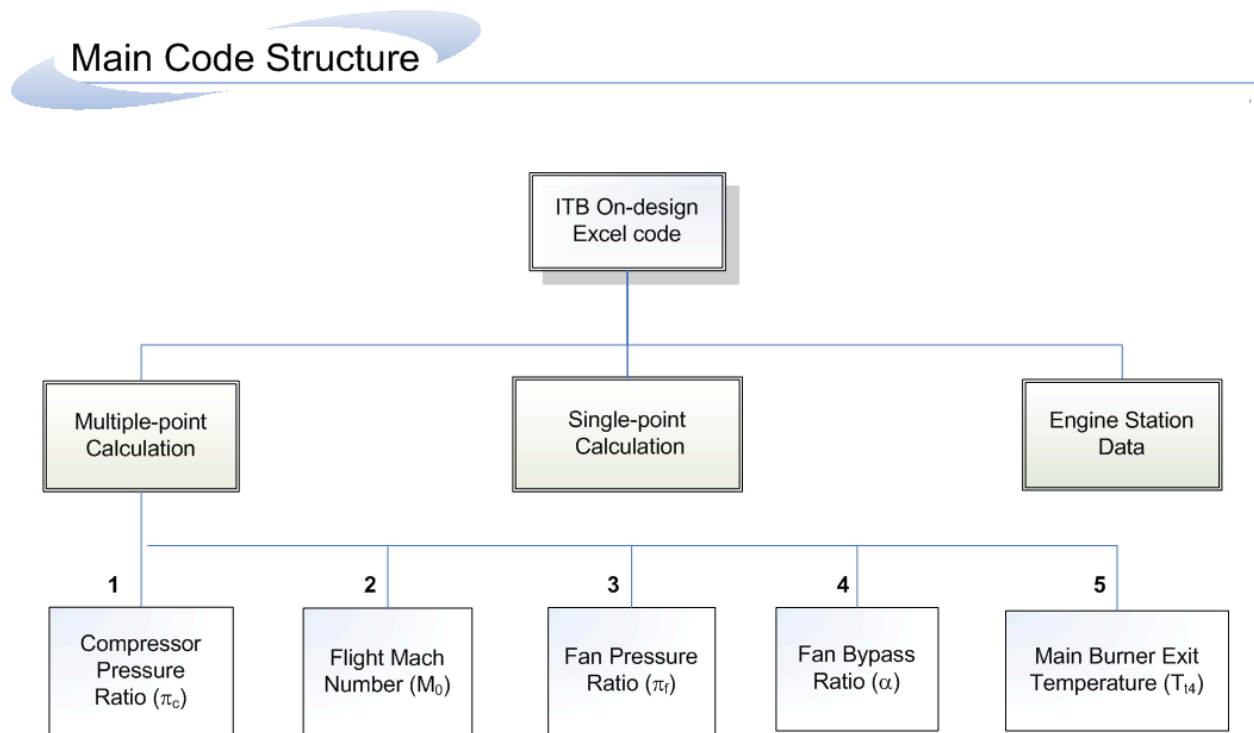# Appendix B—Flowchart of Iterative Solution Scheme in Microsoft® Excel Code

Figure B.1.—Flow-chart of the main structure for *ITB* on-design Microsoft® Excel code.

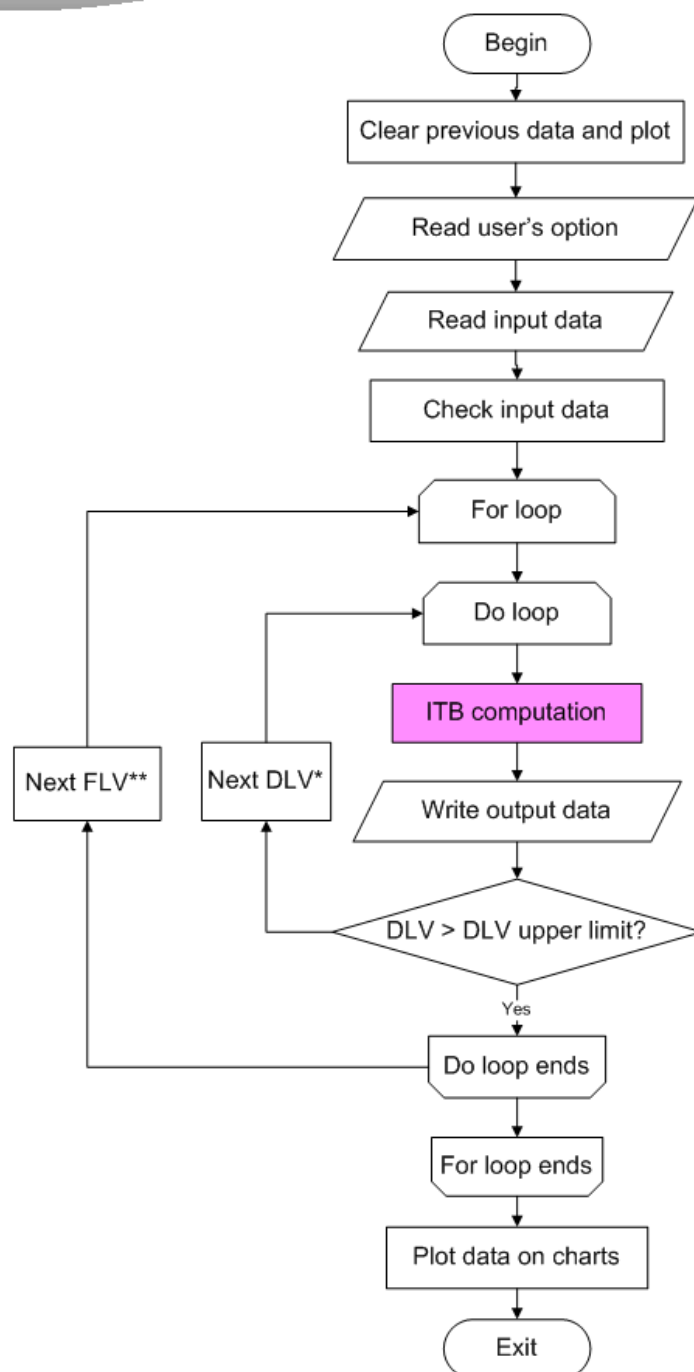# On-design Multiple-point Calculation

Figure B.2.—Flow-chart of the iterative solution scheme for on-design multiple-point calculation.

Remarks: *DLV – Do Loop Variables; **FLV – For Loop Variables.
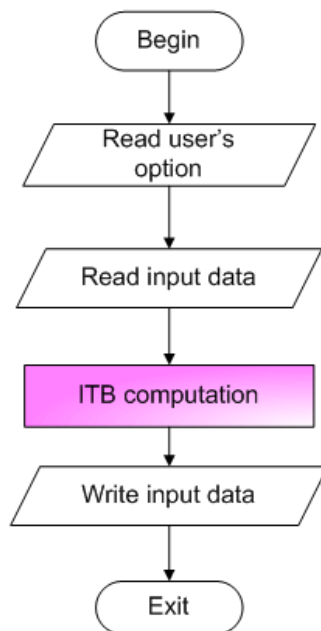
On-design Single Point calculation

Figure B.3.—Flow-chart of the solution scheme for *ITB* on-design single point calculation.

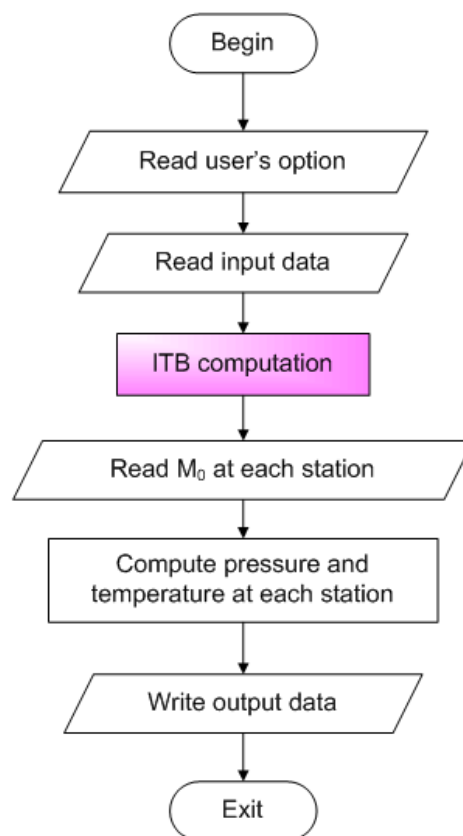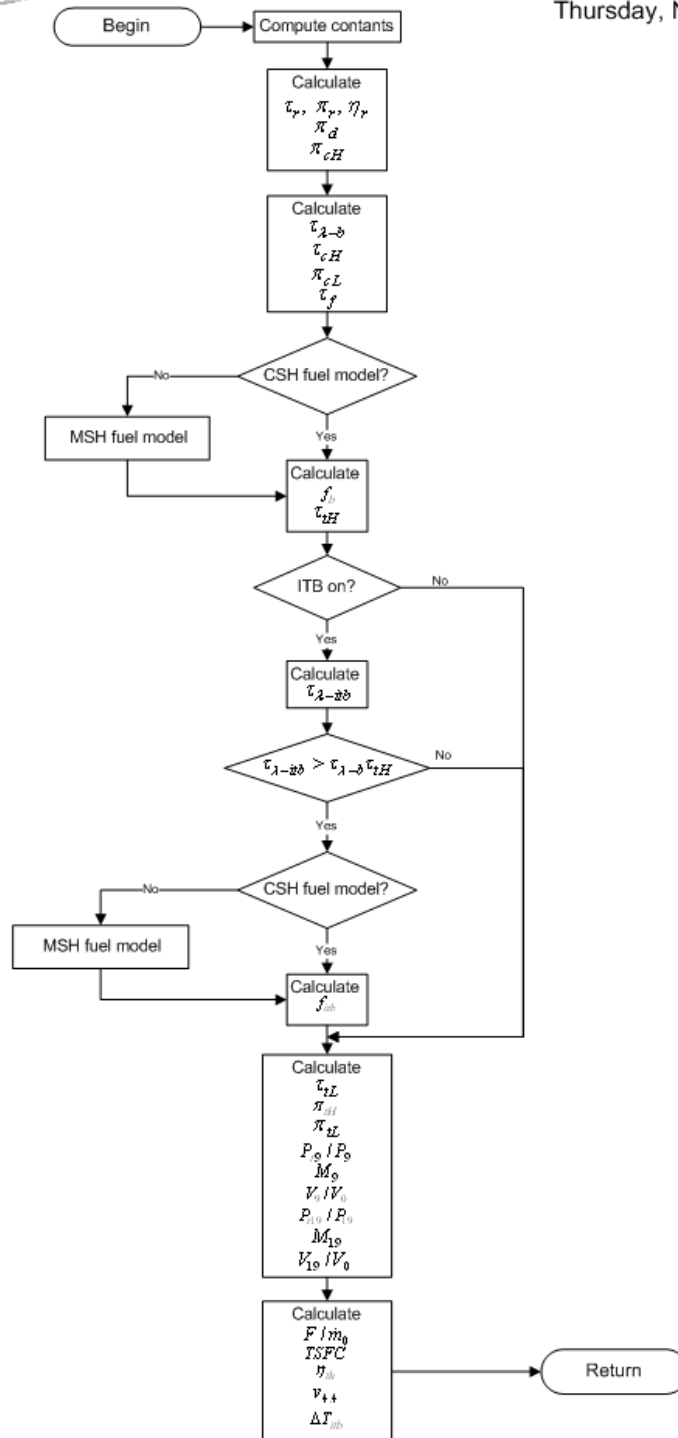Figure B.4.—Flow-chart of the solution scheme for *ITB* engine station data computation.

Figure B.5.—Flow-chart of the iterative solution scheme for *ITB* computation subroutine.

Appendix C—Combustion Fuel Burn Models

C.1 Types of Fuel Burn Models

Two models (p. 116 of ref. 4) are being used to calculate the fuel burned in the main burner and the *ITB*:

(1) **Constant Specific Heat** (*CSH*) model – The air and combustion gases at inlet and exit of each component are modeled as "calorically perfect gases" with constant specific heats. The values of the specific heats are different at inlet and exit of two combustors (main burner and *ITB*)

(2) **Modified Specific Heat** (*MSH*) model – All engines properties are calculated using *CSH* model except the fuel used. In this model, the inlet total temperature (T_{t3} and $T_{t4.4}$) of combustors are calculated using *CSH* model while the exit total temperatures (T_{t4} and $T_{t4.5}$) are directly obtained from the user inputs. Nevertheless, the total enthalpies (h_{t3}, h_{t4}, $h_{t4.4}$, and $h_{t4.5}$) will be calculated directly from the *Variable Specific Heat* (*VSH*) model (p. 116 of Ref. 4). Provided h_{PR} is given, the amount of fuel burned is then calculated using eq. (B4) and (B7), respectively. Therefore, the improvement on enthalpy calculation gives better estimates of fuel used.

The following *ENTHALPY* subroutine is based on pages 105–106 of reference 3 and used in the *MSH* model to calculate the enthalpy (h) at engine stations t3, t4, t4.4, and t4.5.

Subroutine Enthalpy
ENTHALPY ($0,T,f,h,0,0$)
Inputs: T and f
Output: h

$$h_{air} = \left[h_{ref} + A_0 T + \frac{A_1}{2} T^2 + \frac{A_2}{3} T^3 + \frac{A_3}{4} T^4 + \frac{A_4}{5} T^5 + \frac{A_5}{6} T^6 + \frac{A_6}{7} T^7 + \frac{A_7}{8} T^8 \right]_{air} \quad \text{(C.1)}$$

$$h_{prod} = \left[h_{ref} + A_0 T + \frac{A_1}{2} T^2 + \frac{A_2}{3} T^3 + \frac{A_3}{4} T^4 + \frac{A_4}{5} T^5 + \frac{A_5}{6} T^6 + \frac{A_6}{7} T^7 + \frac{A_7}{8} T^8 \right]_{prod} \quad \text{(C.2)}$$

$$h_{mix} = \frac{h_{air} + f h_{prod}}{1 + f} \quad \text{(C.3)}$$

where the constants A_0, etc. are given in Table C.1 (p.106 of Ref. 3).

Table C.1.—Constants for air and combustion products used in subroutine ENTHALPY($0, T, f, h, c_p, \gamma$).

Constant	Air alone	Combustion products of air and $(CH_2)_n$ fuels
A_0	2.5020051×10^{-1}	7.3816638×10^{-1}
A_1	$-5.1536879 \times 10^{-5}$	1.2258630×10^{-5}
A_2	6.5519486×10^{-8}	$-1.3771902 \times 10^{-8}$
A_3	$-6.7178376 \times 10^{-12}$	$9.9686793 \times 10^{-12}$
A_4	$-1.5128259 \times 10^{-14}$	$-4.2051104 \times 10^{-14}$
A_5	$7.6215767 \times 10^{-18}$	$1.0212913 \times 10^{-18}$
A_6	$-1.4526770 \times 10^{-21}$	$-1.3335668 \times 10^{-21}$
A_7	$1.0115540 \times 10^{-25}$	$7.2678710 \times 10^{-25}$
h_{ref}	-1.7558886 Btu/lbm	30.58153 Btu/lbm

The equations needed to calculate the fuel-air ratios of the main burner (f_b) and the *ITB* (f_{itb}) are listed below for both the *CSH* and *MSH* models.

Main burner
If *CSH* model then

$$f_b = \frac{\tau_{\lambda-b} - \tau_{cL}\tau_{cH}}{\eta_b h_{PR}/h_0 - \tau_{\lambda-b}} \tag{C.4}$$

Else

$$T_{t3} = T_0\, \tau_r \tau_{cL} \tau_{cH} \tag{C.5}$$

ENTHALPY $\left(0, T_{t3}, 0, h_{t3}, 0, 0\right)$

Set initial value of fuel/air ratio at station 4 $= f_{4i}$

3   **ENTHALPY** $\left(0, T_{t4}, f_{4i}, h_{t4}, 0, 0\right)$

$$f_b = \frac{h_{t4} - h_{t3}}{\eta_b\, h_{PR} - h_{t4}} \tag{C.6}$$

If $\left|f_b - f_{4i}\right| > 0.0001$, then $f_{4i} = f_b$ and go to 3; else continue.
End if

Inter-stage Turbine Burner
If *CSH* model then

$$f_{itb} = \left(1+4i\right)\frac{\tau_{\lambda-itb} - \tau_{\lambda-b}\tau_{tH}}{\eta_{itb}\, h_{PR}/h_0 - \tau_{\lambda-itb}} \tag{C.7}$$

Else

$$T_{t4.4} = T_{t4}\tau_{tH}$$

ENTHALPY $\left(0, T_{t4.4}, f_b, h_{t4.4}, 0, 0\right)$

Set initial value of fuel/air ratio at station 4.4 $= f_{4.5i}$

4   **ENTHALPY** $\left(0, T_{t4.5}, f_{4.5i}, h_{t4.5}, 0, 0\right)$

$$f_{itb} = \left(1+f_b\right)\frac{h_{t4.5} - h_{t4.4}}{\eta_{itb}h_{PR} - h_{t4.5}} \tag{C.8}$$

If $\left|f_b + f_{itb} - f_{4.5i}\right| > 0.0001$, then $f_{4.5i} = f_b + f_{itb}$ and go to 4; else continue.
End if

If $f_{itb} = 0$ then $\gamma_{itb} = \gamma_t, C_{pitb} = C_{pt}$, and $R_{itb} = R_t$

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3. Mattingly, J.D., "Elements of Gas Turbine Propulsion," McGraw Hill, Inc. New York, NY 1996.
4. Mattingly, J.D., Heiser, W.H., and Pratt, D.T., *Aircraft Engine Design, Second Edition*, AIAA Education Series, AIAA, Reston, VA, 2002.

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13. ABSTRACT *(Maximum 200 words)*

This study focuses on a parametric (on-design) cycle analysis of a dual-spool, separate-flow turbofan engine with an Interstage Turbine Burner (*ITB*). The *ITB* considered in this paper is a relatively new concept in modern jet engine propulsion. The *ITB* serves as a secondary combustor and is located between the high- and the low-pressure turbine, i.e., the transition duct. The objective of this study is to use design parameters, such as flight Mach number, compressor pressure ratio, fan pressure ratio, fan bypass ratio, and high-pressure turbine inlet temperature to obtain engine performance parameters, such as specific thrust and thrust specific fuel consumption. Results of this study can provide guidance in identifying the performance characteristics of various engine components, which can then be used to develop, analyze, integrate, and optimize the system performance of turbofan engines with an *ITB*. Visual Basic program, Microsoft® Excel macrocode, and Microsoft® Excel neuron code are used to facilitate Microsoft® Excel software to plot engine performance versus engine design parameters. This program computes and plots the data sequentially without forcing users to open other types of plotting programs. A user's manual on how to use the program is also included in this report. Furthermore, this stand-alone program is written in conjunction with an off-design program which is an extension of this study. The computed result of a selected design-point engine will be exported to an engine reference data file that is required in off-design calculation.

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